Propane Storage

Report on Hazard and Risk Assessment of Propane Storage on Garage Forecourts

City of Toronto
Planning & Development Department

Robert E. Millward
Commissioner

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1

Overview

1.1 Introduction

Recently, the public demand for propane, as a fuel for vehicles, has increased dramatically. The relatively lower cost of propane as compared to that of the conventional motor car gasoline is one reason for an increased demand. This has necessitated the ready availability of propane to the consumer. In response to this there has been an increase in the number of propane filling units installed at the so-called 'corner gas stations'. However, these 'corner gas stations' were originally designed solely for gasoline and not for propane. Unlike gasoline, propane is a gas at room temperature. If loss of containment occurs, the problem arises of the relative magnitude of the new hazard. A breach of containment for gasoline leads to a running liquid and a restricted vapour cloud, whereas with propane the fuel gasifies and is likely to spread over a greater area. Entrenched positions have been taken in relation to the hazards of these fuels which is a common development for most new innovations. Objective assessment of the situation that may arise from both failure of equipment and maloperation is, therefore, required.

1.2 Objective

The objective of this project is to assess the types and magnitude of hazards involved with a propane tank and the ancillary equipment used at a propane filling station and to determine the risk from the consequences of these hazards.

1.3 Hazards

Although there are many hazards involved with propane refuelling stations, the loss of containment of propane is the initiating event. In general, the hazards involved are asphyxiation, fire and explosion. The risk of these hazards occurring is a function of frequency and magnitude of the hazard and is expressed by the following:

$$Risk = Frequency \times Magnitude$$

The frequency of failure of the tank and its ancillary equipment along with the probability of damage by an external force must be examined in order to determine the frequency of a hazard. The magnitude of the hazard is a function of the magnitude and mode of release of propane.

In installations of this type, there are low frequency high consequence events and higher frequency lower consequence events. Failure of containment of the storage tank exemplifies the first group. Although it should be a low frequency event it represents the worst possible hazard. Examination is justified on these grounds. Amongst the events in the second category are both failures and accidental damage to items of ancillary equipment such as pumps, hoses and valves.

The results of these events are varied in terms of hazards that may be produced. These include:

a) an unconfined vapour cloud explosion (UVCE)
b) a boiling liquid expanding vapour explosion (BLEVE)
c) a fireball
d) a tank fire
e) a pool fire
f) a flash fire
g) a jet flame
h) a confined explosion

Each of these is discussed in detail in section 2.2.

The consequences of these hazards include some or all of the following:

i) blast waves and windage
ii) missiles produced directly and those arising from windage
iii) flame impingement on both materials and persons
iv) thermal radiation
    - burns
    - effects on buildings
v) asphyxiation

The risks of these hazards may be quantified in terms of probability of death, injury, and damage as a function of distance from the source.

The results of loss of containment of propane from the vessel depend on the following:

- physical properties of propane
- flammable properties of propane
- temperature and pressure of propane prior to release

- quantity, type and duration of release
- position and nature of point of release
- time interval between release and ignition
- proximity of buildings and personnel with respect to point of release

All of these must be considered to determine the magnitude and probability of each hazard in order to evaluate the risk involved with the hazards.

1.4 Mathematical Modelling

1.4.1 Fires and Explosions

Mathematical models of fires and explosions vary considerably with respect to the physical and chemical aspects of the combustion system. As a result, many approximations are made in the formulation of these models. In order to use the predicted values to best advantage, appreciation of these assumptions must be realized.

The models for fires predict the thermal radiation intensity from the flame at a specified distance. Fire normally grows by direct burning, which results from impingement of the flame on combustible materials, by heat transfer or by travel of burning material. The three main modes of heat transfer are: conduction, convection and radiation. All of these modes are significant in heat transfer from fires. However, radiation is the most significant mode of heat transfer in a 'free field'.

Explosion is a sudden release of energy. The violence of explosion depends on the rate at which energy is released. There are several kinds of energy which may be released in an explosion. Three basic types are: physical, chemical and nuclear.

1.4.2 Dispersion

The nature of emission and vapourization processes determines the dispersion situation to be considered. There are basically two types of releases; high kinetic energy releases and low kinetic energy releases. If the material comes out as a jet with high kinetic energy then mixing with air is very rapid. But, if the kinetic energy of the material is low then, depending on whether the source is continuous or instantaneous, it will form a puff or plume in which mixing with the surrounding air is comparatively slow.

With respect to dispersion modelling, there are two types of gases; those with a density close to that of air and those gases that have a density greater than air, i.e. light and heavy gases. Methane is an example of a light gas and propane is an example of a heavy gas.

1.4.2.1 Heavy Gas Dispersion

The dispersion of a gas cloud is influenced if the density of the gas/air mixture differs from that of air. This density difference will affect the behaviour of the cloud only if the

concentration of the gas is sufficiently high. A heavy cloud behaves differently from a light one in several respects. It spreads both downwind and upwind; it is flatter in shape and the mechanism of the mixing with air is different. The formation of a gas cloud which is heavier than air depends on the following:

(i) molecular weight
(ii) temperature of gas
(iii) presence of spray
(iv) temperature and humidity of ambient air

The significance of ambient air conditions is that the gas, if cold, will chill the air and cause moisture in the air to condense and form a mist.

The rate of dispersion of a heavy gas depends on the following:

(i) rate of release
(ii) density of gas
(iii) sunshine
(iv) roughness of ground
(v) temperature of ground (or water)
(vi) wind
(vii) atmospheric turbulence

There are four main stages of dispersion of heavy gases. They are: release stage, slumping, entrainment of air and heating of 'slumped layer' by ground.

There are four main types of models that have been produced for computing concentration profiles from dispersion. The models are:

(a) 3-D numerical models wherein the gradient transfer hypothesis for turbulence is used. They are used to simulate non-uniform terrain or obstacles to the flow.
(b) Intermediate (or slab models) – spatial variation of concentration and other quantities in one or two horizontal dimensions are resolved; remaining dimensions are treated as in box models.
(c) Box models – involve gravity slumping but differ in their treatment of air entrainment. All box models assume the initial cloud of vapour to be described by a circular cylinder.
(d) Physical modelling – there is active research in this area. Many problems remain before it can be applied to practical situations.

2

Theoretical Background

2.1 Propane

Basic physical properties:

Chemical Formula: C_3H_8

Molecular Weight: 44.11 g/mol

Boiling Point: -42.1°C

Propane which is a gas at room temperature, is heavier than air e.g.

vapour density at 30°C is 1.773 kg/m^3

vapour density at -10°C is 2.043 kg/m^3.

Thus, depending on the mode of release, any one of the following may result:

(i) propane/air cloud
(ii) stratified propane
(iii) unmixed propane cloud
(iv) pools of liquid propane

Propane is a highly flammable gas with a lower and upper flammability limit (LFL and UFL) of approximately 2.1% and 10.1% in air (% by volume), respectively.

Propane is also classified as a simple asphyxiant. This means that in the event of a release of propane into the atmosphere, the propane would displace the air which contains the oxygen necessary for survival. It does not irritate skin or eyes, but direct contact with liquid propane causes burns and frostbite. Concentrations of propane in air below 1000 ppm exert very little physiological action in human beings. However, changes in animal behaviour have been observed at concentrations above 1000 ppm.

2.2 Types of Hazards

2.2.1 Unconfined Vapour Cloud Explosion (UVCE)

The first step in the formation of a UVCE is the rapid release of a combustible fluid from containment. Upon release from the vessel to the atmosphere, the fluid, if liquid, begins to flash, resulting in the formation of a two-phase stream leaving the vessel. This two-phase flow is turbulent and, as it leaves the pressure vessel, it entrains air. The released mixture forms a flammable unconfined aerial vapour cloud. The speed and the direction of movement of this cloud is dependent on meteorological conditions and obstacles in the path of the cloud. The vapour cloud disperses as it travels, thus decreasing in concentration with time. If the cloud 'finds' a source of ignition and is of sufficient magnitude an explosion could occur resulting in a blast wave, the effects of which depend, inter alia, on the amount of material in the flammable region. However, a blast wave will not form if the cloud is insufficient to allow for adequate flame acceleration to occur. The delay time, (i.e. time from release to the time of ignition), can be up to 20 minutes. On the other hand, if no immediate source of ignition is found, the cloud may disperse sufficiently to render it non-flammable, in which case no UVCE would occur.

2.2.2 Boiling Liquid Expanding Vapour Cloud Explosion (BLEVE) and Fireballs

Basically a BLEVE involves phase change; this is the source of explosive energy. A BLEVE can occur when a vessel containing liquified gas under pressure is exposed to either direct or indirect heating from an external source. Such heating, from a fire for example, could result in failure of the vessel due to a combination of increased internal pressure and/or weakening of the vessel material. The liquified gas is then violently released to the atmosphere where it may be ignited immediately, if it is flammable, thus producing a fireball. A BLEVE may also result from the local failure of the storage vessel by mechanical means e.g. impact. If a subsequent fireball is to be formed, a prompt source of ignition is required. A non-combustible material can also form a BLEVE, but no fireball. The consequences from a BLEVE include overpressure, missiles and tub-rocketing. Missiles could present an additional hazard to our particular situation. If they were to hit the propane tank truck during the refuelling process, the magnitude of the consequences could be greatly increased. The hazard presented by a fireball is that of intense thermal radiation.

2.2.3 Tank Fire

The first step in the formation of a propane tank fire is the release of a combustible pressurized liquid material from a failed pressure vessel. The material begins to flash upon release from the vessel to the atmosphere. This flashing process is endothermic. As a result, the rate of flashing decreases, until the liquid cools down to its boiling point,

at which point the flashing process ceases. The remaining liquid in the tank, would then form a tank fire if it was ignited.

It is necessary for much of the section of the tank to be opened for this event to occur.

2.2.4 Pool Fire

For a pool to be produced from propane storage, the containment must be breached below the liquid level. The material would partially flash as it left the pressure vessel producing a two-phase flow. Thereby cold propane (at less than -42.1°C) will be produced and this fluid will fall to the ground. Upon impact some of the fluid will evaporate and thereby the ground will be cooled. If the quantity of release is of sufficient magnitude, the ground is cooled to below -42.1°C and a pool of liquid propane forms. Introduction of a source of ignition at this stage leads to a pool fire. These events are dependent upon the magnitude and rate of release of the propane and on the nature of the impacted surface. It is likely that for a pool of propane to occur a release of major proportions will be necessary.

2.2.5 Flash Fire

There are two types of flash fires; the stratified flash fire and the pre-mixed flash fire. The mode of release of the pressurized liquid to the atmosphere, whether laminar or turbulent, is the defining factor in determining the type of flash fire formed.

2.2.5.1 Stratified Flash Fire

The first step in forming a stratified flash fire is the slow laminar release of a small amount of vapour in a stable atmosphere. A slow leak from either a failed valve or one that is not tight-closed at night is a reasonable example of this situation. This release would form an unmixed stratified gaseous layer along the ground. As this layer moved slowly along the ground the top 'surface' of the layer would mix with air. If a source of ignition was 'found' then the edge of the cloud would begin to burn, resulting in turbulence which would then disturb the unburnt gas and lead to its ultimate combustion. In view of the fact that propane is pressurized throughout the refuelling system, it seems unlikely that this event could occur.

2.2.5.2 Pre-Mixed Flash Fire

For a pre-mixed flash fire, the rate of release of pressurized liquid must be greater than that in a stratified flash fire. For example, if a valve stem was to break-off it could result in the formation of a turbulent momentum jet which would entrain air to form a well-mixed vapour cloud. This cloud would then travel along the ground. If a source of ignition was 'found', then a flame front would be formed. The flame would travel through the mixture and its velocity, which is of the order of tens of metres per second, will be greater than the rate of combustion in a stratified flash fire. Therefore, the

duration of exposure to a pre-mixed flash fire is shorter than it is for a similar sized stratified flash fire. However, a percussive deflagration may be produced thereby generating overpressure.

2.2.6 Jet Flame

Jet fires result from ignition of either gaseous or two-phase discharges of combustible fluid from high pressure containment. Such discharges could occur through leakages in the pumps, pipes, valves and at emergency vents. Upon release of the material, air becomes entrained into the jet because of the turbulence induced from the high pressure release. Then, depending on the operating conditions, the jet fire would stabilize at or above the point of discharge. The main hazards involved with jet fires are thermal radiation and flame impingement. Other hazards include: toxic products of combustion, smoke and noise.

2.2.7 Confined Explosion

A confined explosion could result from the release of a pressurized propane from a failed pressure vessel. The released material would flash to form a vapour cloud as in 2.2.1. This vapour cloud would then disperse as it travelled. However, the cloud, depending on meteorological conditions and on topography, could find its way into a confined space. For example, the cloud could travel through an open garage door into a building. Such a cloud would then be confined and could, therefore, no longer disperse. If this confined mixture were of flammable concentration then, if ignited, a confined explosion would occur. It is important to note that the danger in this type of explosion is the inability of a confined flammable mixture to disperse. The delay time to ignition can be several hours. The hazards involved with confined explosions are overpressure and missiles. These could in fact destroy the building in which the explosion took place. Even if the confined mixture was too fuel-rich for combustion there could be a hazard of asphyxiation.

2.2.8 Asphyxiation

If propane was released from a pressure vessel and was not ignited, then the possibility of asphyxiation would exist. If someone was in close proximity to the tank at time of release, the concentration of propane could be great enough to cause the victim to be asphyxiated i.e. prior to dispersion of the cloud of propane.

2.3 Gasoline

The hazards associated with gasoline will also be evaluated in order to compare them with propane.

Gasoline is comprised of a variety of chemical compounds, many of which are C-6 to C-9 hydrocarbons. The manufacturers also add a variety of performance enhancing additives to gasoline to promote cleaner and more efficient combustion. The amount and type of these additives depend on the temperature at which the gasoline will be used; therefore, gasoline varies in composition from season to season. Since the actual composition of gasoline varies significantly, hexane, (C-6), was chosen as a representative compound for gasoline.

Basic physical properties of hexane:

Chemical Formula: C_6H_{14}

Molecular Weight: 86.18 g/mol

Boiling Point: 69°C

Gasoline is highly flammable. It has a lower and upper flammability limit of 1.25% and 7.0% in air (% by volume), respectively.

2.4 Gasoline Hazards

2.4.1 Tank Fire

Gasoline tanks at filling stations are generally situated underground. As a result, it is unlikely that during normal usage the top of the tank would be breached allowing a tank fire to form. Therefore, the probability of obtaining a tank fire is small. However, the use of heavy machinery for excavation in close proximity to a buried tank may damage it. If this damage is extensive enough and if a source of ignition is 'found', then a tank fire could result. Furthermore, the fact that gasoline tanks are usually buried, leaves them open to corrosive attack and thence may cause leakage. This problem has been estimated to be of major proportions in the U.S.A and Canada.

2.4.2 Pool Fire

The failure of a component in the pumping system could result in the release of gasoline. If such a release was great enough, then a liquid pool of gasoline would form on the ground. If a source of ignition was 'found' then a gasoline pool fire could result.

2.4.3 Jet Flame

If a small hole developed in a gasoline pumping system during operation e.g. in a transfer line or a pump, then a jet of gasoline would be emitted from the hole. If this fine jet 'found' a source of ignition, then a jet fire would result.

2.4.4 Confined Explosion

If a release of gasoline was to occur on an impermeable sloped surface, such as concrete, then the liquid travels in the direction of the slope. This pool could travel underneath a door into an enclosed area. The gasoline would vapourize, and, depending on the size of the confined space, could form a flammable mixture. If this mixture was subsequently ignited a confined explosion could occur.

3

Analysis of Hazards at Propane Filling Stations

Each of the hazards of propane, listed above, will be analyzed individually in the context of a propane storage tank which is situated on a garage forecourt. For comparative purposes the hazards associated with propane will be compared to those of gasoline.

Propane storage tanks are available in several different sizes. In order to simplify calculations, one standard tank size was chosen for the purposes of the hazard analysis. The tank chosen was a 5 000 USWG (18 927 L) vertical cylindrical tank which is one of the more common storage tanks in use. Other tank sizes which are in common use are the 2 000 USWG and the 3 000 USWG tanks. The process flow diagram for a typical propane storage tank is shown in Figure 1.

In order to take into account the variations in meteorological conditions, calculations were performed at two different temperatures and under wind and no-wind conditions. The two values of temperature were chosen viz 30°C and -10°C which are representative of summer and winter conditions. Where applicable, calculations were performed at both the 2 m/s representative wind speed and for the no-wind condition. Although actual wind conditions dramatically vary from street corner to street corner in a large urban centre, comparison of the results obtained from the 2 m/s wind condition and no-wind condition give an indication of the general wind effect on the magnitude of safety separation distances. However, the pattern of flow in urban areas is very complex and it involves both high ground-level wind speeds and gusting. Also, the relative humidity was assumed to be zero unless otherwise specified.

The calculations used to determine the magnitude and effects of the hazards at these two temperatures are shown in Appendix I.

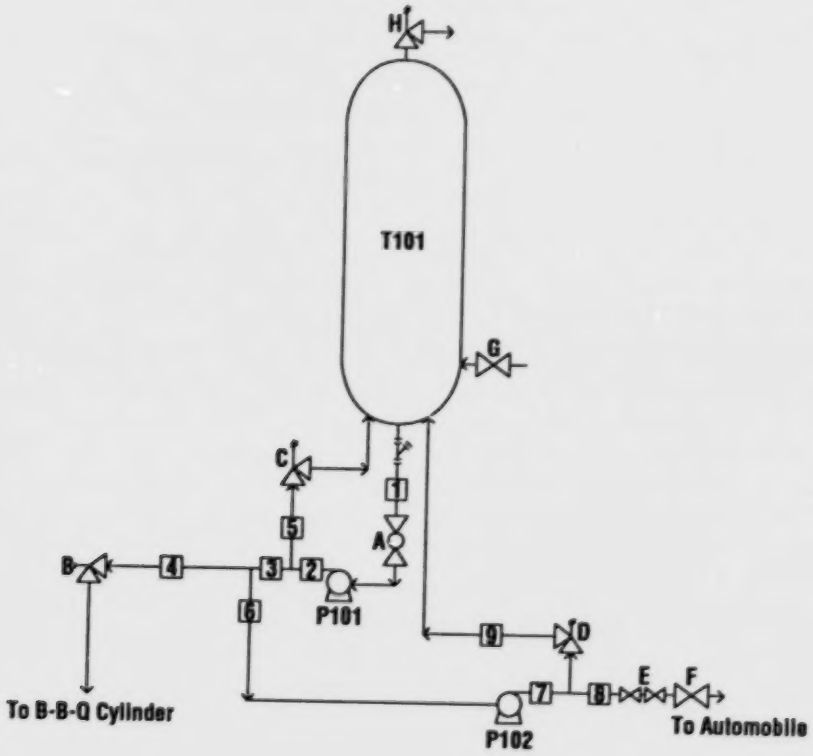
Figure 1
Propane Tank Process Flow Diagram

P101
2.24 kW (3 H.P.)
Differential Pressure:
585 kPa (85 psi)

T101
Height: 7.33 m
Diam.: 1.83 m
Design Pressure:
1720 kPa (250 psi)

P102
Dispenser
Delivery Pressure:
275 kPa (40 psi)
Delivery Rate:
40 L/min.

Note: Ambient Operating Temperature



Line and Valve List for Figure 1.

Line **Comments**

1. transfer line from storage tank to pump: flexible, armoured rubber (diameter: 2.54 x 10^{-2} m (1 in.)) at 1720 kPa (250 psi)
2. pump exit line:carbon steel (diameter: 3.18 x 10^{-2} m (1¼ in.))
3. transfer line from pump exit line to angle valve (B): carbon steel (diameter: 1.91 x 10^{-2} m (¾ in.))
4. barbecue tank dispenser line:flexible, armoured rubber (diameter: 1.91 x 10^{-2} m (¾ in.)) at 275 kPa (40 psi)
5. recirculation line from pump: flexible, armoured rubber (diameter: 1.91 x 10^{-2} m (¾ in.))
6. transfer line from pump to dispenser: flexible, armoured rubber and copper line (diameter: 1.91 x 10^{-2} m (¾ in.))
7. internal dispenser line:carbon steel (diameter: 1.91 x 10^{-2} m (¾ in.))
8. automobile dispenser line: flexible, armoured rubber (diameter: 2.54 x 10^{-2} m (1 in.)) at 275 kPa (40 psi)
9. recirculation line from dispenser: copper and flexible, armoured rubber (diameter: 1.91 x 10^{-2} m (¾ in.))

Valve

A. manual operated globe valve: (3.81 x 10^{-2} m (1 ¼ in.)) for propane feed from storage tank to pump

B. manual operated angle valve: (3.81 x 10^{-2} m (1 ¼ in.)) for barbeque dispenser line

C. by-pass valve: from to pump to storage tank

D. by-pass valve: from dispenser to storage tank

E. break-away coupling

F. valve end: dispenser nozzle (diameter: 1.91 x 10^{-2} m (¾ in.))

G. filling valve: (diameter: 5.01 x 10^{-2} m (2 in.))

H. pressure relief valve: (diameter: 5.01 x 10^{-2} m (2 in.))

4

Types of Failure

As stated in section 1.3 the hazard analysis of a propane refuelling installation involves incidents of two types viz low frequency high consequence events and those of higher frequency and lower consequence. In this section the topic will first be exemplified and then a listing of breaches of containment will be given with estimated sizes of the breaches.

High probability events arise from the failure of ancilliary equipment or components thereof e.g. leaking joint due to gasket failure or failed pump-seal. Such failures will result in the release of limited quantities of propane and may not result from normal usage. Some limited releases may result from either maloperation or damaging treatment of parts of the installation e.g. release of propane during the 'round-up' of refuelling or a limited rupture of a hose by inflicted damage. The subsequent effects of such breaches depend on both the position of the breach (and, therefore, the layout) and on the rapidity with which steps can be taken to mitigate the effects of the release. It must also be recognized that one of these 'small-scale' releases may escalate to a major failure. This is exemplified by a flame impinging on the storage tank which then fails and releases its contents.

A low probability failure could result from a large truck or a crane colliding with the side of the tank with sufficient momentum to cause either immediate tank rupture or the tank to be knocked over with subsequent rupture on impact with the ground. The result of such an incident occurring can be classified as a major tank failure. Although, such an event is unlikely, there is always the chance that it may happen. Another incident leading to major tank failure would be the impact of a missile resulting from the occurrence of a possible neighbouring hazard. The effects of corrosion may also lead or contribute to tank failure. Catastrophic failure of the tank may result from the effects discussed here.

The types of high probability failures, along with the respective openings that may occur at a propane filling station are listed in Table 1.

Table 1
Opening Size From Component Failure (Diameter of Equivalent Circle)

Component	Failure	Opening Size (Diameter of Equiv. Circle (m))
Pump	Gasket Seal or 'O' Rings	2.53×10^{-3}
	Impeller Seal	2.83×10^{-2}
	Pipe Joint Threading	1.27×10^{-3}
Valve	Seat or Seal	7.08×10^{-3}
	Stem Knocked Off	1.91×10^{-2}
	Pipe Joint Threading	1.27×10^{-3}
Lines		
Rubber Automobile Dispenser Hose	Break-Away Coupling \ Nozzle > Fractured Hose /	2.54×10^{-2}
Rubber Barbecue Dispenser Hose	Nozzle Fractured Hose	1.91×10^{-2}
Pump Lines	Fractured Line	
	(Into Pump)	2.54×10^{-2}
	(Out of Pump)	3.18×10^{-2}
Dispenser	Fractured Internal Piping	1.91×10^{-2}
Pressure Relief Valve	Failed Open	5.01×10^{-2}

The low probability failures can be classified into one category, which is major tank failure. The types of incidents and/or conditions leading to major tank failure are listed in Table 2.

Table 2
Incidents and/or Conditions Leading to Major Tank Failure

1) Impact from Collision with other than Tank Truck
2) Impact from Collision with Tank Truck
3) Overheating due to Flame Impingement
4) Overfilling
5) Spontaneous Failure due to:
   - Corrosion of Tank Skin
   - Stress Cracking

N.B. Corrosion may contribute to failure in (1) to (4).

5

Consequences

Both high and low probability failures have a variety of consequences which could result from breach of containment. Generally, the consequences from a low probability failure are greater than those from a high probability failure.

There are three main consequences that can result from the aforementioned failures. They are: overpressure, thermal radiation and asphyxiation. Both overpressure and thermal radiation may have secondary consequences. The secondary consequence from overpressure is that of missiles. Major tank failure due to overpressurization caused by thermal radiation would also be a secondary consequence.

Overpressure produces a blast wave, the energy of which is dissipated into the surroundings as it travels, in the ideal case, in concentric spheres from the source. The distance travelled by the blast is a function of the total energy in the initial source, the greater this initial energy the further the distance travelled by the blast wave. The blast wave will cease to travel once it has dissipated all of its energy. As this wave travels it may 'pick-up' objects such as mail boxes or even human beings and turn them into missiles. The distance travelled by these missiles depends on their physical characteristics and the amount of energy they receive from the blast wave.

All objects can withstand a certain level of overpressure before they 'fail' or 'break'. This overpressure can be termed as the critical overpressure of the object. For example, a typical house window, could withstand an overpressure of approximately 700 Pa or 0.1 psi before it shatters. The thicker the glass pane and the smaller the size of the window, the greater the overpressure that the window can withstand. Some windows can withstand a peak overpressure of 1 700 Pa or 0.25 psi.

Obviously, the distance from the source at which the window will 'fail' depends on the initial amount of energy available for the formation of the blast wave. This leads to the idea of separation distance between the source and the target, i.e. the distance from the source at which the target will not 'fail'. The greater the initial energy available for the formation of the blast wave the greater the separation distance between the source and target. In Table 3 the critical overpressures for several resultant effects are listed (Brasie and Simpson [3]).

Table 3
Effects of Overpressure

Resultant Effects at Specified Overpressure	Overpressure at the Location (kPa / psi)
10% Window Glass Breakage	0.7 / 0.1
50% Structural Damage	19 / 2.8
50% Eardrum Rupture	43 / 6.3
50% Mortality	140 / 20.0

The second major consequence of concern is that of thermal radiation. Thermal radiation can be the consequence of both high and low probability failures. The radiative flux received by the target depends on the size and energy of the source, the separation distance between the source and target, the duration of exposure and the emissivity of the source. As the separation distance between the source and the target increases, the dose received by the target during a given period of time decreases. For a given target at a specified distance, there is an allowable safe maximum exposure duration to a specified dose which should not be exceeded. There is, then, a 'trade-off' between exposure duration and separation distance. The method used to relate these quantities is Probit analysis (Finney [9]). Probit analysis relates the intensity of some phenomenon (causative factor) such as thermal radiation or overpressure to the degree of injury or damage which can result from it.

The maximum flux intensities and the respective exposure durations that can be received by the target of concern are listed in Table 4 (Crocker and Napier [7]).

Table 4
Thermal Radiation Effects at Incident Flux

Vulnerable Target	Radiation Intensity (kW/m^2)	Exposure Time (s)	Observed Effect
People	4.7	15	Threshold of Pain
Buildings	12.6	44	Pilot Ignition of Plastic Cables,Cellulose Materials
Storage Tank	37.8	1000	Hazardous for Tank to Receive Flux

The third major consequence is asphyxiation. There are two types of asphyxiants; simple and chemical asphyxiants. Propane is a simple asphyxiant which displaces or dilutes the oxygen in the air necessary for survival.

Asphyxiation is a threat to human life only if the released propane is not immediately ignited. Once ignited, the hazard of asphyxiation is replaced by either overpressure or thermal radiation. If a release of propane is not immediately ignited, then the cloud of propane will disperse in the atmosphere. A minimum concentration of 6% oxygen in air is necessary for survival. Therefore, the cloud will be considered as non-asphyxiant if the concentration of oxygen in the cloud is above 6%. Although asphyxiation may not occur at concentration above 6%, a person's decision and judgement-making ability will be increasingly affected as oxygen concentration is reduced below 17%.

Each hazard may have more than one consequence attributed to it. The hazards, along with their respective consequence(s) are listed in Table 5.

Table 5
Hazards and Their Consequences

Hazard	Consequence
a) UVCE	Overpressure, Missiles
b) BLEVE	Overpressure, Missiles, Tub-Rocketing
c) Fireball	Thermal Radiation
d) Pool/Tank Fire	Thermal Radiation, Flame Impingement, Flame Drag
e) Flash Fire	Thermal Radiation, Flame Impingement
f) Jet Flame	Thermal Radiation, Flame Impingement on both Materials and Persons
g) Confined Explosion	Overpressure, Missiles

6

Probability

6.1 Failure Rates

In order to determine the risk of a hazard, the frequency with which that hazard occurs must be known. This frequency is dependent on the probability that the particular component leading to that specified hazard will fail. The probability of failure of a particular component or equipment can be expressed in terms of a failure rate. Each component or particular equipment has a specified failure rate. The values for the failure rates of particular equipment are listed in data bases. The values listed in the data bases are based on past experience.

The failure rates used for this particular study were obtained from Green and Bourne [11], Lees [15] and from Canvey [12]. The failure rates for the credible failures are listed in Table 6.

Table 6
Component Failure Rates

Component	Failure	Failure Rate (failures/year)
Pump	Gasket Seal	4.38×10^{-3}
	or 'O' Rings	1.75×10^{-3}
	Impeller Seal	6.13×10^{-2}
	Threading	3.50×10^{-3}
Valve	Seat or Seal \	
	Stem Knocked Off >	4.38×10^{-3}
	Threading /	
Lines		
Rubber Automobile	Break-Away Coupling	4.38×10^{-2}
Dispenser Hose	Nozzle	4.38×10^{-2}
	Fractured Hose	3.50×10^{-2}
Rubber Barbecue	Nozzle	4.38×10^{-2}
Dispenser Hose	Fractured Hose	3.50×10^{-2}
Pump Lines	Fractured Line	3.50×10^{-2}
Dispenser	Fractured	
	Internal Piping	1.75×10^{-3}

The failure rates for the vessel which would lead to major tank failure are listed in Table 7.

Table 7
Failures Rates for Storage Tank Failure

Incidents and/or Conditions Leading to Major Tank Failure	Failure Rate (failures/year)
1) Impact from Collision with other than Tank Truck	4.38×10^{-4}
2) Impact from Collision with Tank Truck	2.63×10^{-5}
3) Overheating due to Flame Impingement	5.26×10^{-5}
4) Spontaneous Failure due to: \ - Corrosion of Tank Skin > - Stress Cracking /	8.76×10^{-5}

N.B. The values of (1) to (3) will be modified by the effect of corrosion.

6.2 Ignition

Even though a failure producing an ignitable mixture may occur, this does not necessarily mean that the mixture will ignite. The mixture may disperse until it is rendered non-flammable at which point it would no longer be a hazard. Therefore, the probability of ignition must be taken into consideration. Ignition probabilities are listed in Table 8 (Canvey [13]):

Table 8
Ignition Probabilities

Sources of Ignition	Ignition Probabilities
'None'	0.1
Very Few	0.2
Few	0.5
Many	0.9

The following are examples of these:

'None': 'None readily identifiable' example, limited release of hydrocarbon into a bund after overfilling a tank.

Very Few: Large release of gas liquified under pressure after a major failure of a tank in a tank farm.

Few: Release of a flammable material near to non-continuous operations, example, LPG release from a tank near to road/rail facilities.

Many: Release of flammable material near to a plant or a release resulting from a nearby fire or explosion.

For purposes of this study the probability of ignition will be taken as 0.5.

In specific locations where there are, as in normal, a multiplicity of sources of ignition, there is a requirement to consider the probability of ignition by the total distribution of sources. Thus the probability, P_n, of ignition of a flammable cloud, at the n^{th} source of ignition, is equal to the ignition probability per source, i, (here 0.5) multiplied by the probability that the ignition does not occur at the other (n-1) sources already encountered, i.e.

$$P_n = i(1-i)^{n-1}.$$

For an explosion, such as an UVCE, to occur there is an added consideration to be made. That is the probability of explosion after the mixture has ignited. For this study the probability of explosion will be taken as 0.1.

7

Risk Assessment

The method of assessment was to identify and analyse from first principles the routes by which an accident or accidents could effect the community. It was thought that a quantitative approach was the best way of comparing different risks. The probability of the different modes of failures and their respective range of consequences were quantified; thus risks could be quantified. Determining risks numerically provides one with a common denominator, thus allowing meaningful comparison between different risks.

Risk has also been defined as the probability of an event occurring, i.e. the probability of the accident itself or the probability of the defined consequence. Risk can also be expressed as individual risk and societal risk.

Individual risk is the probability of the individual's being killed as a result of the types of accident under consideration. The individual risk is a measure of the general level of danger. Thus, individual risk will vary depending on where the person is in relation to the accident. Societal risk can be defined in terms of the number of people who would be killed in a single accident, and the probability that this will occur. It is the probability that a single accident may cause more than a specified number of deaths.

The actual value of risk can be determined by using the following:

Risk = Frequency of Hazard x Magnitude of the Hazard

or in the terms

Risk = Frequency of Hazard x Potential for Harm x Expected Degree of Exposure

The frequency of the hazard is determined by the probability of failure of the vessel or the particular component of concern and the chain of events following the failure, e.g. release, dispersion and ignition, leading to the specified hazard. These probabilities are listed in the previous section 5.0.

The magnitude of the hazards were quantified by modelling each of the hazards of concern individually and, thereby, calculating safe separation distances between the hazard and the general public. Probit analysis was used in these calculations in order to present the results in a meaningful fashion.

8

Results

The results obtained from this study are shown in the tables and figures that follow. For purposes of clarity, the results from analysis of each hazard are listed individually. Meteorological conditions, at which the results apply, are specified in each table. Calculations performed to achieve these results are detailed in Appendix I.

All of these results are reported without commentary, which is given in the discussion.

N.B. Relative humidity was assumed to be zero, unless otherwise specified.

8.1 Propane Storage Tank

8.1.1 UVCE

Table 9
Overpressure Separation Distances From a UVCE (Propane Storage Tank)

Overpressure Consequence	Overpressure (kPa)	Separation Distance (m) 30°C	-10°C	Consequence Probability (vid. 5.0) (%)
Window Glass Breakage	0.7	1 350	970	10
Structural Damage	19	48	35	50
Eardrum Rupture	43	-	-	50
Mortality	140	-	-	50

Note: Figures 2, 3 and 4 are graphical presentations of Table 9.

Figure 2
UVCE Overpressure (30°C)
Blast Wave Overpressure versus Distance from Cloud Centre

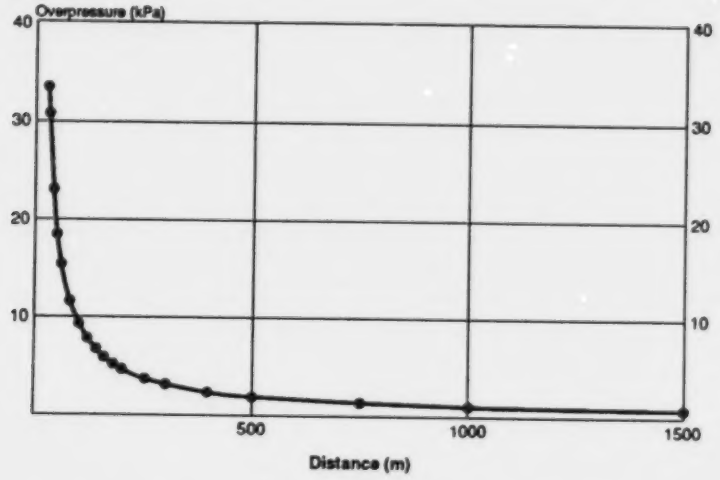


Figure 3
UVCE Overpressure (-10°C)
Blast Wave Overpressure versus Distance from Cloud Centre

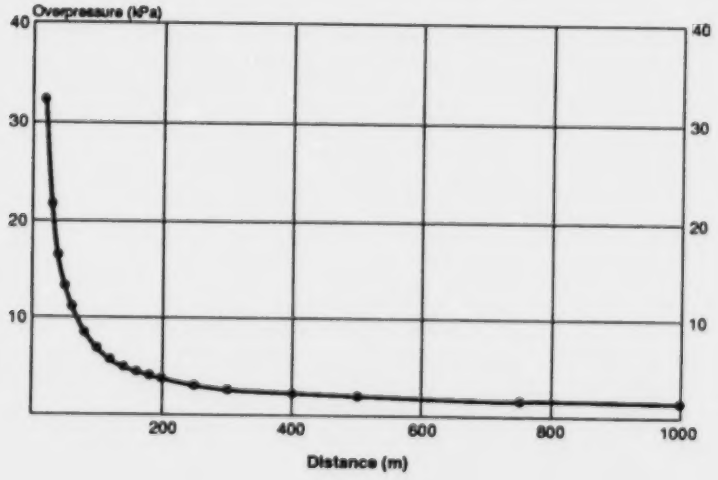
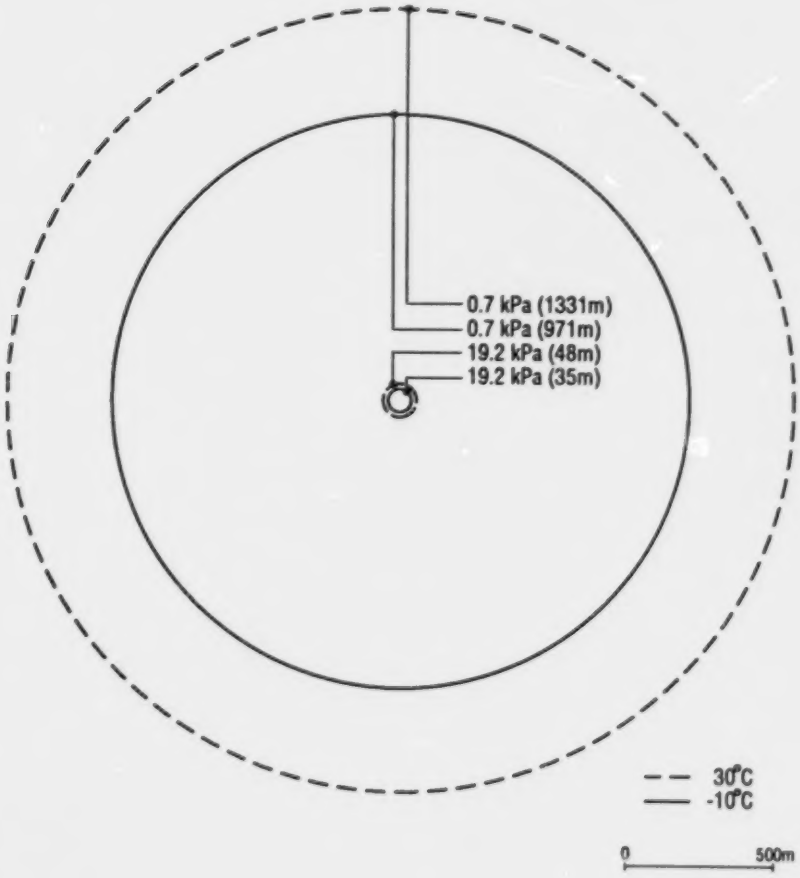


Figure 4
UVCE Overpressure Contours



8.1.2 BLEVE

Table 10
Overpressure Separation Distances From a BLEVE (Propane Storage Tank)

Overpressure Consequence	Overpressure (kPa)	Separation Distance (m) 30°C	-10°C	Consequence Probability (vid. 5.0) (%)
Window Glass Breakage	0.7	240	104	10
Structural Damage	19	12	5	50
Eardrum Rupture	43	6	3	50
Mortality	140	2	-	50

Note: Figures 5, 6 and 7 are graphical presentations of Table 10.

Figure 5
BLEVE Overpressure (30°C)
Blast Wave Overpressure versus Distance from Cloud Centre

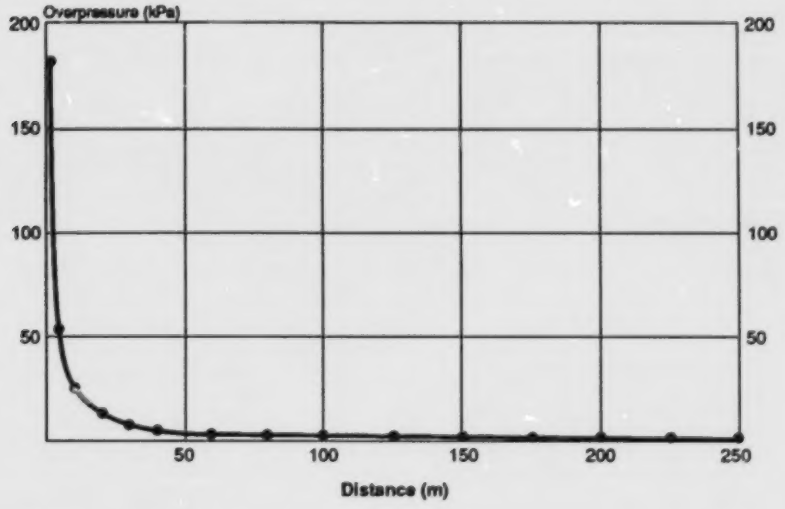


Figure 6
BLEVE Overpressure (-10°C)
Blast Wave Overpressure versus Distance from Cloud Centre

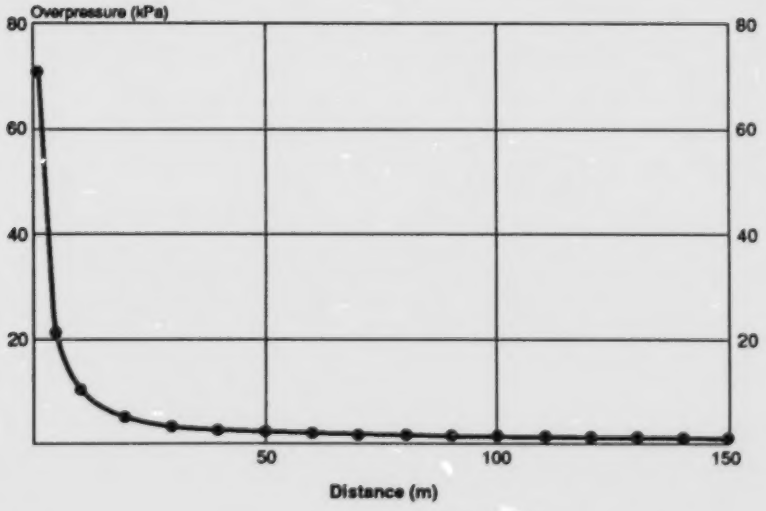
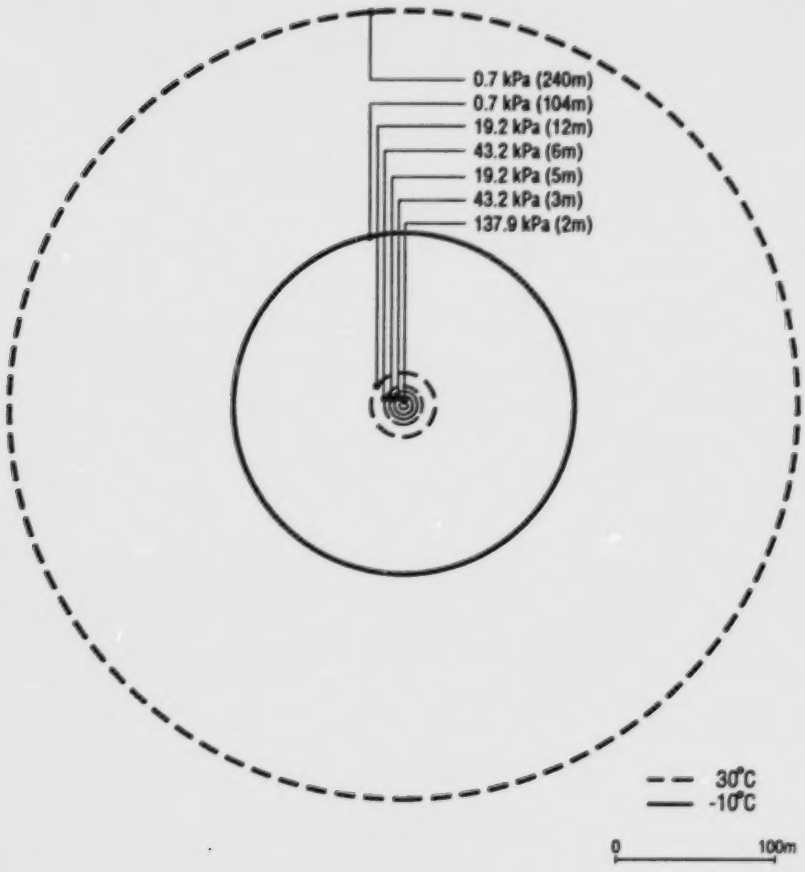


Figure 7
BLEVE Overpressure Contours



8.1.3 Fireball

Table 11
Separation Distances From a Fireball to Avoid Incident Thermal Radiation (Propane Storage Tank)

Incident Radiation Intensity (kW/m^2)	Separation Distance R.H. = 0% 30°C / -10°C (m)	R.H. = 50% 30°C / -10°C (m)
4.7	112 / 8	104 / 85
12.6	69 / 52	64 / 51
37.8	40 / 30	37 / 29

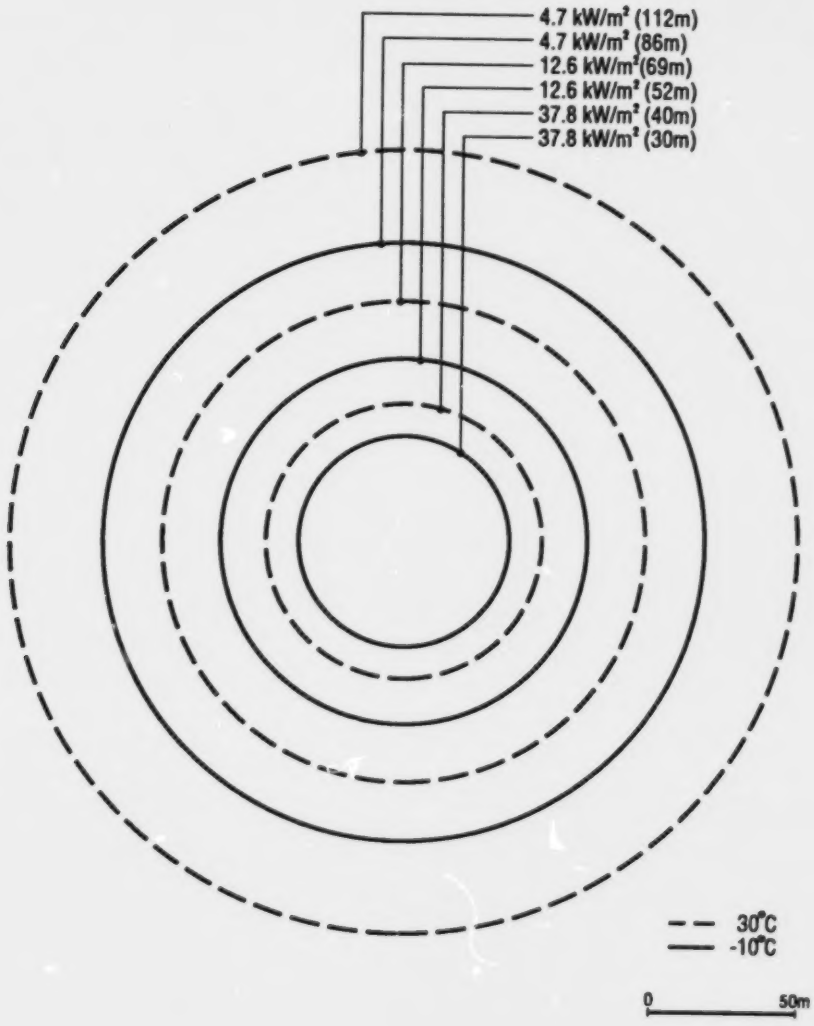
Note: Figure 8 is a graphical presentation of Table 11.

Table 12
Thermal Radiation Consequences From a Fireball (Propane Storage Tank)
For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Ambient Temperature (°C)	Duration of Exposure (s)	Incident Radiation Intensity For Required Dose (kW/m^2)	Limiting Distance From Source For Required Dose (m)
30	4.4	112	23
-10	3.7	127	17

Note: Duration of exposure is the actual duration of the fireball.

Figure 8
Fireball Thermal Radiation Contours



8.1.4 Tank Fire

Table 13
Separation Distances From a Propane Tank Fire to Avoid Incident Thermal Radiation (wind = 0 m/s)

Target	Incident Radiation Intensity (kW/m^2)	Separation Distance (30°C) (m)	(-10°C) (m)
Human Body	4.7	89	86
Buildings	12.6	55	53
Storage Tanks	37.8	32	31

Note: Figure 9 is a graphical presentation of Table 13.

Table 14
Separation Distances From a Propane Tank Fire to Avoid Incident Thermal Radiation (wind = 2 m/s)

Target	Incident Radiation Intensity (kW/m^2)	Separation Distance (30°C) (m)	(-10°C) (m)
Human Body	4.7	90	87
Buildings	12.6	58	55
Storage Tanks	37.8	36	34

Note: Figure 10 is graphical presentation of Table 14.

Figure 9
Tank Fire Thermal Radiation Contours
(Wind = 0 m/s)

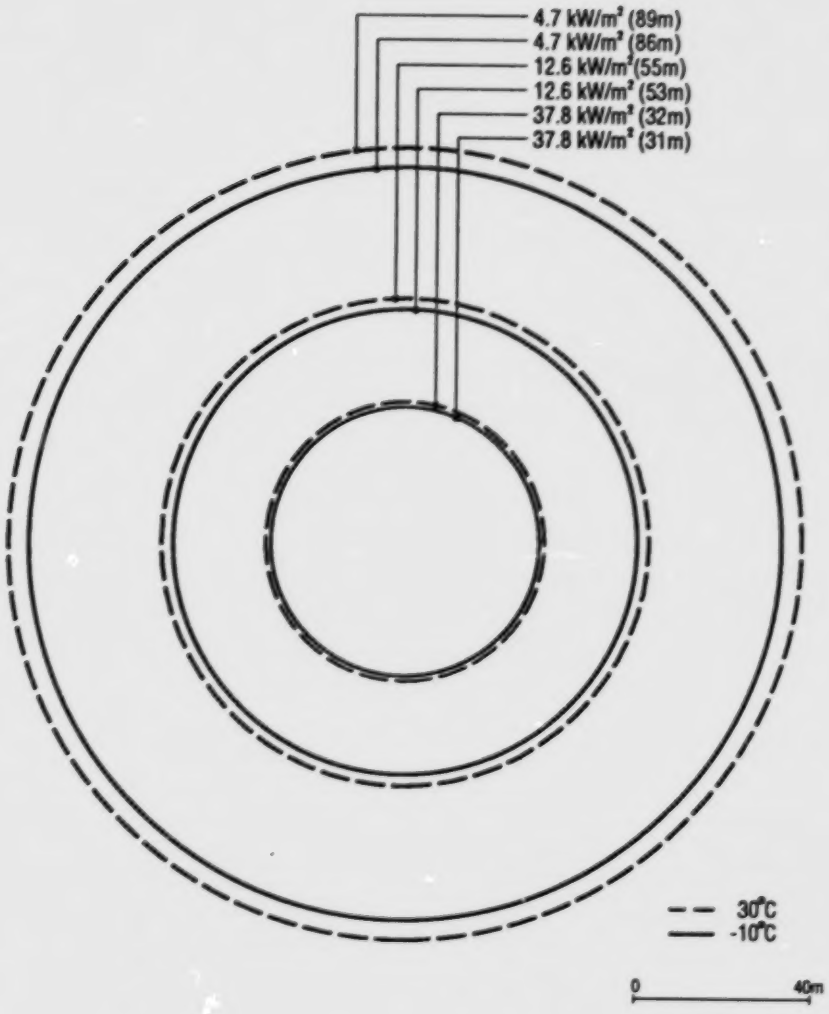


Figure 10
Tank Fire Thermal Radiation Contours
(Wind = 2 m/s)

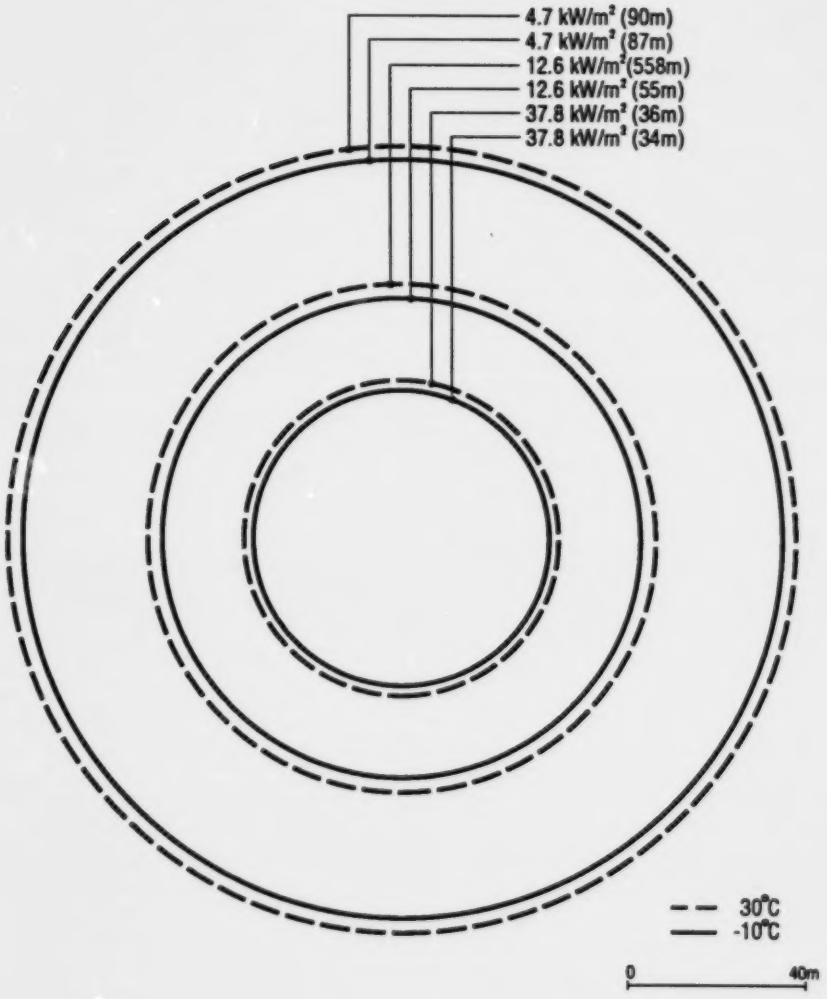


Table 15
Thermal Radiation Consequences from a Propane Tank Fire (wind = 0 m/s)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Ambient Temperature (°C)	Duration of Exposure (s)	Incident Radiation Intensity For Required Dose (kW/m^2)	Limiting Distance From Source For Required Dose (m)
30	15	44.6	29
30	60	15.8	49
-10	15	44.6	28
-10	60	15.8	47

Table 16
Thermal Radiation Consequences From a Propane Tank Fire (wind = 2 m/s)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Ambient Temperature (°C)	Duration of Exposure (s)	Incident Radiation Intensity For Required Dose (kW/m^2)	Limiting Distance From Source For Required Dose (m)
30	15	44.6	33
30	60	15.8	52
-10	15	44.6	31
-10	60	15.8	49

8.1.5 Pool Fire

Table 17
Separation Distances From a Propane Pool Fire to Avoid Incident Thermal Radiation (wind = 0 m/s and Pool Diameter = 2 m)

Target	Incident Radiation Intensity (kW/m^2)	Distance From Source (m) 30°C	-10°C
Human Body	4.7	97	95
Buildings	12.6	59	58
Storage Tanks	37.8	34	34

Table 18
Separation Distances From a Propane Pool Fire to Avoid Incident Thermal Radiation (wind = 0 m/s and Pool Diameter = 5 m)

Target	Incident Radiation Intensity (kW/m^2)	Distance From Source (m) 30°C	-10°C
Human Body	4.7	211	205
Buildings	12.6	129	125
Storage Tanks	37.8	75	72

Table 19
Thermal Radiation Consequences From a Propane Pool Fire (wind = 0 m/s and Pool Diameter = 2 m)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Ambient Temperature (°C)	Duration of Exposure (s)	Incident Radiation Intensity For Required Dose (kW/m^2)	Limiting Distance From Source For Required Dose (m)
30	15	44.6	31
30	60	15.8	53
-10	15	44.6	31
-10	15	15.8	52

Table 20
Thermal Radiation Consequences From a Propane Pool Fire
(wind = 0 m/s and Pool Diameter = 5 m)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Ambient Temperature (°C)	Duration of Exposure (s)	Incident Radiation Intensity For Required Dose (kW/m^2)	Limiting Distance From Source For Required Dose (m)
30	15	44.6	69
30	60	15.8	115
-10	15	44.6	67
-10	60	15.8	112

8.1.6 Flash Fire (Pre-Mixed)

Table 21
Maximum Flammable Cloud Radius for a Pre-Mixed Flash Fire

Diameter of Discharge Area (m)	Maximum Flammable Cloud Radius for a Pre-Mixed Flash Fire (m) (30°C)	(-10°C)
2.53×10^{-3}	15	11
1.91×10^{-2}	154	110
2.83×10^{-2}	242	172

8.1.7 Jet Fire

Table 22
Separation Distances From a Propane Jet Fire to Avoid Incident Thermal Radiation (At 30°C)

Jet Diameter (m)	Flame Length (m)	Separation Distance (m) 4.7 (kW/m²)	12.6 (kW/m²)	37.8 (kW/m²)
1.27×10^{-3}	0.3	2	<1	<1
2.53×10^{-3}	0.5	5	3	1
7.08×10^{-3}	1.6	13	8	5
1.91×10^{-2}	4.3	35	21	12
2.54×10^{-2}	5.7	46	28	16
2.83×10^{-2}	6.4	52	31	18
3.81×10^{-2}	8.6	70	42	24
5.01×10^{-2}	11.3	91	55	32

Table 23
Separation Distances From a Propane Jet Fire to Avoid Incident Thermal Radiation (At -10°C)

Jet Diameter (m)	Flame Length (m)	Separation Distance (m) 4.7 (kW/m²)	12.6 (kW/m²)	37.8 (kW/m²)
1.27×10^{-3}	0.3	2	<1	<1
2.53×10^{-3}	0.6	4	2	1
7.08×10^{-3}	1.7	10	6	4
1.91×10^{-2}	4.6	28	17	10
2.54×10^{-2}	6.2	37	22	13
2.83×10^{-2}	6.9	41	25	14
3.81×10^{-2}	9.2	55	34	19
5.01×10^{-2}	12.1	73	44	25

Note: Figure 11 is a graphical presentation of Tables 21 and 22 for a Jet Diameter 3.81×10^{-2} m.

Figure 11
Jet Fire Thermal Radiation Contours
(Jet Diameter = 0.0381 m)

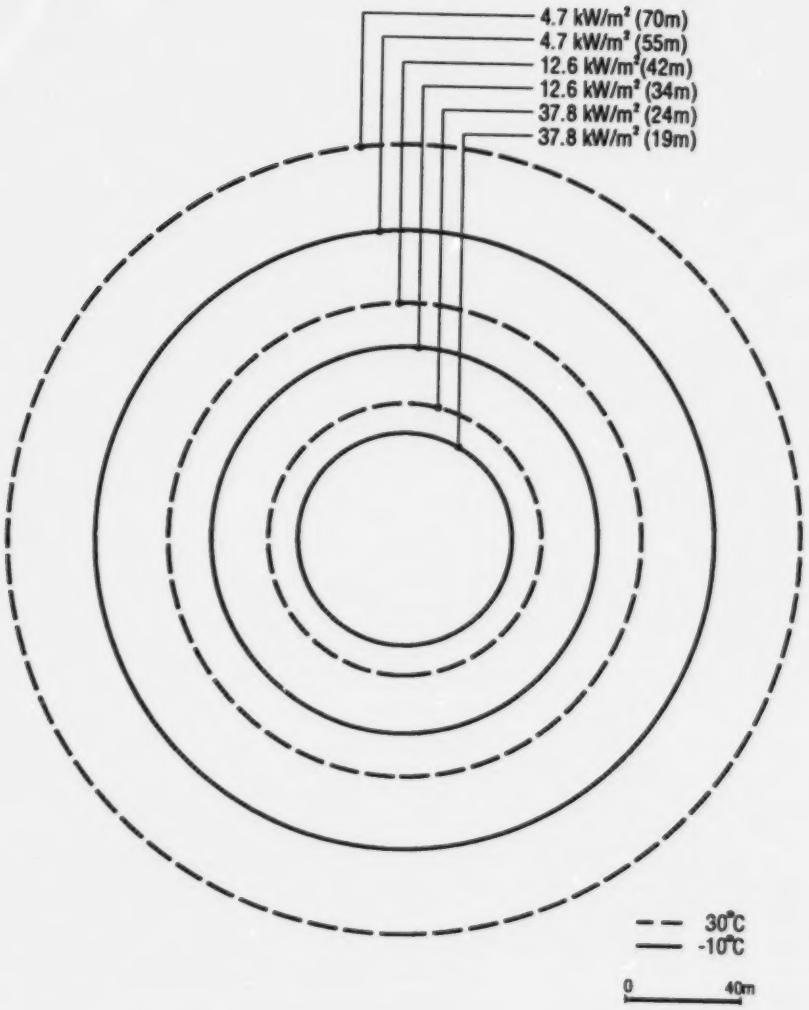


Table 24
Thermal Radiation Consequences From a Propane Jet Fire (At 30°C)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Case A: Exposure Duration: 15 s
Radiation Intensity For Required Dose: 44.6 kW/m^2

Case B: Exposure Duration: 60 s
Radiation Intensity For Required Dose: 15.8 kW/m^2

Jet Diameter (m)	Limiting Distance From Source For Required Dose (m) Case A	Case B
1.27×10^{-3}	<1	<1
2.53×10^{-3}	1	2
7.08×10^{-3}	4	7
1.91×10^{-2}	11	19
2.54×10^{-2}	15	25
2.83×10^{-2}	17	28
3.81×10^{-2}	22	38
5.01×10^{-2}	29	49

Table 25
Thermal Radiation Consequences From a Propane Jet Fire (At -10°C)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Case A: Exposure Duration: 15 s
Radiation Intensity For Required Dose: 44.6 kW/m^2

Case B: Exposure Duration: 60 s
Radiation Intensity For Required Dose: 15.8 kW/m^2

Jet Diameter (m)	Limiting Distance From Source For Required Dose (m) Case A	Case B
1.27×10^{-3}	<1	<1
2.53×10^{-3}	<1	2
7.08×10^{-3}	3	6
1.91×10^{-2}	9	15
2.54×10^{-2}	12	20
2.83×10^{-2}	13	22
3.81×10^{-2}	17	30
5.01×10^{-2}	22	39

8.1.8 Confined Explosion

Table 26
Separation Distance From a Propane Release to Achieve a Cloud Concentration of the Lower Flammability Limit (wind = 2 m/s) (Propane Storage Tank)

Consequence	Separation Distance (m) (to LFL)	
	(30°C)	(-10°C)
LFL	262	177

8.1.9 Asphyxiation

Table 27
Separation Distance From a Propane Release to Avoid Asphyxiation (wind = 2 m/s) (Propane Storage Tank)

Consequence	Separation Distance (m) (to 6% Oxygen in Air (v/v))	
	(30°C)	(-10°C)
Asphyxiation	15	11

8.1.10 Overfilling Automobile Propane Tank

Table 28
Separation Distance to Avoid Asphyxiation From a Propane Release Due to 'Round-Up' Filling of an Propane Automobile Tank (wind = 2 m/s)

Consequence	Separation Distance (m) (to 6% Oxygen in Air (v/v))	
	(30°C)	(-10°C)
Asphyxiation due to Overfilling Automobile Tank	0.5	0.3

8.2 Gasoline

8.2.1 Tank Fire

Table 29
Thermal Radiation Separation Distances from a Gasoline Tank Fire to Avoid Incident Radiation (wind = 0 m/s)

Target	Incident Radiation Intensity (kW/m^2)	Distance From Source (m) 30°C	-10°C
Human Body	4.7	115	113
Buildings	12.6	58	57
Storage Tanks	37.8	33	33

Table 30
Thermal Radiation Consequences From a Gasoline Tank Fire (wind = 0 m/s)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Ambient Temperature (°C)	Duration of Exposure (s)	Incident Radiation Intensity For Required Dose (kW/m^2)	Limiting Distance From Source For Required Dose (m)
30	15	44.6	31
30	60	15.8	52
-10	15	44.6	31
-10	60	15.8	51

8.2.2 Pool Fire

Table 31
Separation Distances From a Gasoline Pool Fire to Avoid Incident Thermal Radiation (wind = 0 m/s and Pool Diameter = 2 m)

Target	Incident Radiation Intensity (kW/m^2)	Distance From Source (m) 30°C	-10°C
Human Body	4.7	102	101
Buildings	12.6	62	61
Storage Tanks	37.8	36	35

Table 32
Separation Distances From a Gasoline Pool Fire to Avoid Incident Thermal Radiation (wind = 0 m/s and Pool Diameter = 5 m)

Target	Incident Radiation Intensity (kW/m^2)	Distance From Source (m) 30°C	-10°C
Human Body	4.7	223	221
Buildings	12.6	135	134
Storage Tanks	37.8	78	77

Table 33
Thermal Radiation Consequences From a Gasoline Pool Fire (wind = 0 m/s and Pool Diameter = 2 m)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Ambient Temperature (oC)	Duration of Exposure (s)	Incident Radiation Intensity For Required Dose (kW/m2)	Limiting Distance From Source For Required Dose (m)
30	15	44.6	33
30	60	15.8	56
-10	15	44.6	32
-10	15	15.8	55

Table 34
Thermal Radiation Consequences From a Gasoline Pool Fire
(wind = 0 m/s and Pool Diameter = 5 m)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Ambient Temperature (°C)	Duration of Exposure (s)	Incident Radiation Intensity For Required Dose (kW/m^2)	Limiting Distance From Source For Required Dose (m)
30	15	44.6	73
30	60	15.8	122
-10	15	44.6	72
-10	15	15.8	121

8.2.3 Jet Fire

Table 35
Separation Distances From a Gasoline Jet Fire to Avoid Incident Thermal Radiation (At 30°C)

Jet Diameter (m)	Flame Length (m)	Separation Distance (m) 4.7 (kW/m^2)	12.6 (kW/m^2)	37.8 (kW/m^2)
1.27×10^{-3}	0.4	<1.0	<1.0	<1.0
2.53×10^{-3}	0.8	1.0	<1.0	<1.0
7.08×10^{-3}	2.2	4	3	1
1.91×10^{-2}	5.8	11	6	3
2.54×10^{-2}	7.8	14	8	4
2.83×10^{-2}	8.6	16	9	4
3.81×10^{-2}	11.6	21	12	6

Table 36
Separation Distances From a Gasoline Jet Fire to Avoid Incident Thermal Radiation (At -10°C)

Jet Diameter (m)	Flame Length (m)	Separation Distance (m) 4.7 (kW/m²)	12.6 (kW/m²)	37.8 (kW/m²)
1.27×10^{-3}	0.4	<1.0	<1.0	<1.0
2.53×10^{-3}	0.8	1.0	<1.0	<1.0
7.08×10^{-3}	2.3	4	2	1
1.91×10^{-2}	6.3	10	6	3
2.54×10^{-2}	8.3	13	8	4
2.83×10^{-2}	9.3	15	9	4
3.81×10^{-2}	12.5	20	11	6

Table 37
Thermal Radiation Consequences from a Gasoline Jet Fire (At 30°C)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Case A: Exposure Duration: 15 s
Radiation Intensity For Required Dose: 44.6 kW/m²

Case B: Exposure Duration: 60 s
Radiation Intensity For Required Dose: 15.8 kW/m²

Jet Diameter (m)	Limiting Distance From Source For Required Dose (m) Case A	Case B
1.27×10^{-3}	<1	<1
2.53×10^{-3}	<1	<1
7.08×10^{-3}	1	2
1.91×10^{-2}	2	5
2.54×10^{-2}	3	7
2.83×10^{-2}	4	8
3.81×10^{-2}	5	10

Table 38
Thermal Radiation Consequences from a Gasoline Jet Fire (At -10°C)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Case A: Exposure Duration: 15 s
Radiation Intensity For Required Dose: 44.6 kW/m^2

Case B: Exposure Duration: 60 s
Radiation Intensity For Required Dose: 15.8 kW/m^2

Jet Diameter (m)	Limiting Distance From Source For Required Dose (m) Case A	Case B
1.27×10^{-3}	<1	<1
2.53×10^{-3}	<1	<1
7.08×10^{-3}	<1	2
1.91×10^{-2}	2	4
2.54×10^{-2}	3	7
2.83×10^{-2}	4	8
3.81×10^{-2}	5	10

8.2.4 Confined Explosion

Table 39
Separation Distance From a Gasoline Release to Achieve a Cloud Concentration of the Lower Flammability Limit
(wind = 2 m/s) (Pool Diameter = 2 m)

Consequence	Separation Distance (m) (to LFL) (30°C)	(-10°C)
LFL	20	14

Table 40
Separation Distance From a Gasoline Release to Achieve a Cloud Concentration of the Lower Flammability Limit
(wind = 2 m/s) (Pool Diameter = 5 m)

Consequence	Separation Distance (m) (to LFL) (30°C)	(-10°C)
LFL	30	22

8.3 Propane Tank Truck

8.3.1 UVCE

Table 41

Overpressure Separation Distances From a UVCE (Propane Tank Truck)

Overpressure Consequence	Overpressure (kPa)	Separation Distance (m) 30°C	-10°C	Consequence Probability (%)
Window Glass Breakage	0.7	2570	1970	10
Structural Damage	19	211	161	50
Eardrum Rupture	43	128	98	50
Mortality	140	64	49	50

8.3.2 BLEVE

Table 42

Overpressure Separation Distances From a BLEVE (Propane Tank Truck)

Overpressure Consequence	Overpressure (kPa)	Separation Distance (m) 30°C	-10°C	Consequence Probability (%)
Window Glass Breakage	0.7	313	177	10
Structural Damage	19	26	15	50
Eardrum Rupture	43	16	9	50
Mortality	140	8	4	50

8.3.3 Fireball

Table 43

Separation Distances From a Fireball to Avoid Incident Thermal Radiation (Propane Tank Truck)

Incident Radiation Intensity (kW/m^2)	Separation Distance (30°C) (m)	(-10°C) (m)
4.7	188	144
12.6	115	88
37.8	66	51

Table 44
Thermal Radiation Consequences From a Fireball (Propane Tank Truck)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Ambient Temperature (°C)	Duration of Exposure (s)	Incident Radiation Intensity For Required Dose (kW/m^2)	Limiting Distance From Source For Required Dose (m)
30	7.4	76	47
-10	5.7	92	33

Note: Duration of exposure is the actual duration of the fireball.

8.3.4 Pool Fire

Table 45
Separation Distances From a Propane Tank Truck Pool Fire to Avoid Incident Thermal Radiation (wind = 0 m/s and Pool Diameter = 10 m)

Target	Incident Radiation Intensity (kW/m^2)	Distance From Source (m) 30°C	-10°C
Human Body	4.7	379	369
Buildings	12.6	232	226
Storage Tanks	37.8	135	131

Table 46
Thermal Radiation Consequences From a Propane Tank Truck Pool Fire (wind = 0 m/s and Pool Diameter = 10 m)

For: Consequence: 50% Lethality
Required Dose: 2375 $s(kW/m^2)^{4/3}$

Ambient Temperature (°C)	Duration of Exposure (s)	Incident Radiation Intensity For Required Dose (kW/m^2)	Limiting Distance From Source For Required Dose (m)
30	15	44.6	124
30	60	15.8	209
-10	15	44.6	121
-10	15	15.8	202

8.3.5 Asphyxiation

Table 47
Separation Distance From a Propane Tank Truck Release to Avoid Asphyxiation (wind = 2 m/s)

Consequence	Separation Distance (m) (to 6% Oxygen in Air (v/v)) (30°C)	(-10°C)
Asphyxiation	26	19

8.4 Risk of Hazards

The risks listed below are individual risk to a person situated in an clear line of sight from the hazard i.e. no obstructions between the individual and the hazard.

8.4.1 Propane Storage Tank

Table 48
Individual Risk for 50% Mortality from Propane Storage Tank Hazards

Hazard	Conditions	Distance From Hazard for 50% Mortality (30°C)	(-10°C)	Individual Risk At Specified Distance (risk/year)
UVCE		-	-	-
BLEVE		2	-	5.26×10^{-5}
Fireball		23	17	2.63×10^{-5}
Tank Fire	Wind: 0 m/s Exposure: 15 s	29	28	2.19×10^{-4}
	Wind: 0 m/s Exposure: 60 s	49	47	2.19×10^{-4}
	Wind: 2 m/s Exposure: 15 s	33	31	2.19×10^{-4}
	Wind: 2 m/s Exposure: 60 s	52	49	2.19×10^{-4}
Pool Fire	Wind: 0 m/s Exposure: 15 s Pool Dia: 2 m	31	31	2.19×10^{-2}
	Wind: 0 m/s Exposure: 60 s Pool Dia: 2 m	53	52	2.19×10^{-2}
	Wind: 0 m/s Exposure: 15 s Pool Dia: 5 m	69	67	2.19×10^{-2}
	Wind: 0 m/s Exposure: 60 s Pool Dia: 5 m	115	112	2.19×10^{-2}
Jet Fire	Wind: 0 m/s Exposure: 15 s Jet Dia: 0.0381 m	22	17	2.19×10^{-2}
	Wind: 0 m/s Exposure: 60 s Jet Dia: 0.0381 m	38	30	2.19×10^{-2}

8.4.2 Gasoline

Table 49
Individual Risk for 50% Mortality from Gasoline Storage Tank Hazards

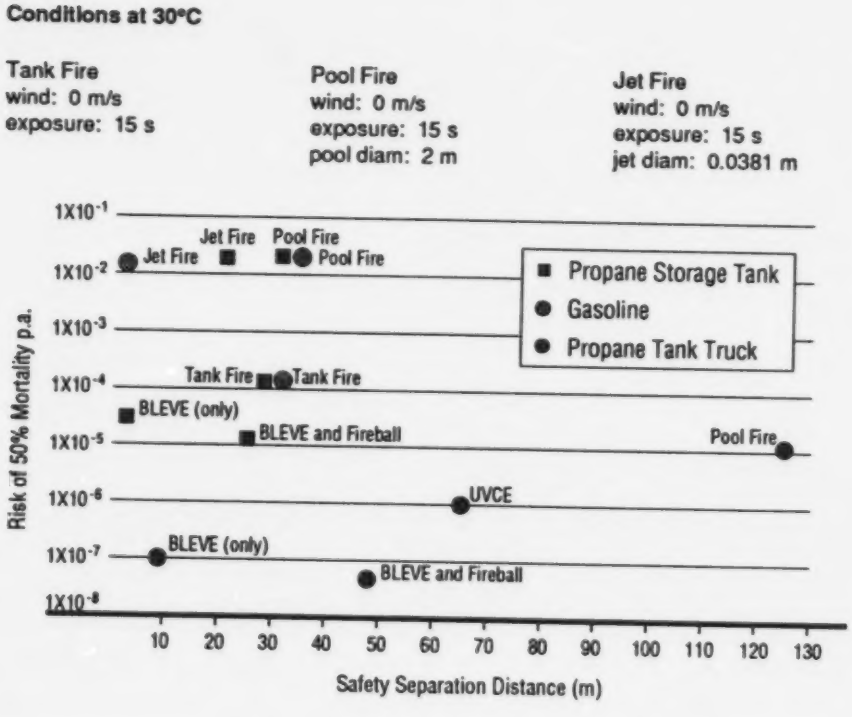
Hazard	Conditions	Distance From Hazard For 50% Mortality (30°C)	(-10°C)	Individual Risk At Specified Distance (risk/year)
Tank Fire	Wind: 0 m/s Exposure: 15 s	31	31	2.19×10^{-4}
	Wind: 0 m/s Exposure: 60 s	52	51	2.19×10^{-4}
Pool Fire	Wind: 0 m/s Exposure: 15 s Pool Dia: 2 m	33	32	2.19×10^{-2}
	Wind: 0 m/s Exposure: 60 s Pool Dia: 2 m	73	72	2.19×10^{-2}
	Wind: 0 m/s Exposure: 15 s Pool Dia: 5 m	122	121	2.19×10^{-2}
	Wind: 0 m/s Exposure: 60 s Pool Dia: 5 m	115	112	2.19×10^{-2}
Jet Fire	Wind: 0 m/s Exposure: 15 s Jet Dia: 0.0381 m	5	5	1.75×10^{-2}
	Wind: 0 m/s Exposure: 60 s Jet Dia: 0.0381 m	10	10	1.75×10^{-2}

8.4.3 Propane Tank Truck

Table 50
Individual Risk for 50% Mortality from Propane Tank Truck Hazards

Hazard	Conditions	Distance From Hazard For 50% Mortality (30°C)	(-10°C)	Individual Risk At Specified Distance (risk/year)
UVCE		64	49	1.31×10^{-6}
BLEVE		8	4	1.58×10^{-7}
Fireball		47	33	7.90×10^{-6}
Pool Fire	Wind: 0 m/s Exposure: 15 s Pool Dia: 10 m	124	121	1.31×10^{-5}
	Wind: 0 m/s Exposure: 60 s Pool Dia: 2 m	209	202	1.31×10^{-5}

Figure 12
Key Information from Tables 48, 49 and 50
(The plotted values correspond to the risk at the limiting value of separation distance for the pertinent consequences)



9

Discussion

9.1 General Comments

The mathematical models of explosions and fires used in this study were chosen carefully in order to best approximate the situation of concern. The use of these models necessitated the assumption of physical and chemical aspects of the combustion system. Thus, the values obtained from these models are approximations and must therefore be utilized in the light of the assumptions made and the validation undertaken.

The main assumption of this report is that the propane storage tank is situated in a free field, i.e. no obstructions in close proximity to the tank. This assumption provides general guidance on the consequences of dispersion, fire and explosion, but no account is taken of the detailed arrangement and the surroundings at any specific filling station. In order to do so, the stations would have to be examined singly when the effects of layout, of surrounding structures and of proximity to dwellings and traffic would be considered. For example, a neighbouring building could provide shelter from thermal radiation or overpressure and thereby reduce an individual's risk to that particular hazard. On the other hand, such stations provide a degree of containment so that dispersion of the release of propane is limited; thereby the effects of blast and thermal radiation are modified. Clearly effects of these structures vary from station to station and the safety separation distances will alter from one location to another.

Another factor that can have an effect on the applicability of the results is the variety of meteorological conditions such as changes in ambient temperature, precipitation, relative humidity, wind direction and velocity and, even, the time of day. All of these modify the magnitude and mode of release and hence the magnitude of safety separation distances from a particular hazard. To take account of some of these effects, the analysis of the hazards was performed at two different temperatures. Furthermore, where applicable, some of the calculations were performed under wind and no wind conditions to further simulate actual operating conditions. However, it must be noted that local wind direction and velocity at any particular urban station can change

dramatically from one instant to the next depending on the proximity and size of neighbouring structures. Velocities of local ground winds are as much dependent on the prevailing wind and temperature as they are on the distribution and type of surrounding structures. For all thermal radiation calculations, the relative humidity was assumed to be zero. However, for comparative purposes, the relative humidity for the propane fireball situation was taken as both zero and 50%. The effect of atmospheric transmissivity is discussed later.

Corrosion is another factor to be considered. In the City of Toronto large amounts of salt are used in winter to help combat the hazards of icy roads. This salt can cause increased corrosion to the skin of the storage tank in the same way that salt increases the rate of corrosion in an automobile. This corrosion could increase the probability of tank failure. Corrosion and contamination with extraneous material, of components such as valves and fittings are also a concern. The effects of corrosion can increase the rate of component failure.

Another important point to be noted is that of the size of storage tank selected. The 5 000 USWG tank which was selected as the tank size for this study will necessitate greater safety separation distances than those required for the smaller 2 000 USWG and 3 000 USWG tank sizes. The hazards associated with the reduced inventory, i.e. the smaller tanks, will result in consequences that are less in magnitude than those of the larger 5 000 USWG tank. Consequently the safety separation distances for overpressure, thermal radiation and asphyxiation will be less in magnitude for the smaller storage tanks.

An important point to note is that, although the magnitude of consequences is less for the smaller tank size, the probability of hazards involving the tank truck is greater since the smaller tanks require more frequent refuelling.

Each of the hazards will now be discussed in detail to explain the results obtained.

9.2 Propane Storage Tank

9.2.1 UVCE

The separation distances at which specified damage from a UVCE could occur are listed in Table 9. Figures 2 and 3 show a graphical representation of these results and Figure 4 illustrates the overpressure contours at which specified damage could occur.

The minimum amount of a flammable hydrocarbon, such as propane, required for a UVCE is not precisely known. The main criterion for the formation of a UVCE depends on the size of flammable cloud. This must be large enough to provide the flame acceleration needed to produce overpressure. In the Canvey Report [13] it is suggested

that the minimum amount of fuel required for a UVCE is approximately 5000 kg. However, this is only an estimate; it is not known whether or not a UVCE can be formed under certain conditions with a smaller amount of fuel.

If the tank failed catastrophically, the amount of propane vapour released would be 3 447 kg and 1 530 kg at 30°C and -10°C, respectively. This would result in flammable cloud sizes of 1 296 m^3 and 499 m^3, at the two aforementioned temperatures. Based on the values from the Canvey Report [12 and 13], it does not seem likely that a UVCE would form in the present situation. However, it can be said that although the probability of forming a UVCE under these conditions is small, it is not zero. If a UVCE was to occur it would be more likely at 30°C than at -10°C because of the increased quantity of fuel released at the higher temperature.

The probability of a UVCE occurring with the smaller propane tanks (2 000 USWG or 3 000 USWG) is much smaller than that for the 5 000 USWG. The decrease in inventory with the smaller tanks results in the formation of smaller flammable clouds insufficient in size to promote an explosion.

From the results obtained it was found that a change in ambient temperature has an effect on the magnitude of separation distances. Releases at the higher temperature (30°C) requires greater separation from the source of hazard for a specified level of overpressure damage than that for the lower temperature (-10°C). The reason for this is that the greater the ambient temperature, the greater is the vapour pressure in the storage tank and the greater is the fraction of vapour released upon vessel failure. The more vapour that is released the greater is the amount of propane available for the UVCE and, therefore, there is an increase in the overpressure obtainable from an explosion. For example, the distance for the occurrence of 10% window breakage is 1350 m at 30°C and 970 m at -10°C, a difference of 380 m. Structures impeding or redirecting the path of the blast front could decrease the safety separation distances required for a specified effect. For example if a UVCE was to occur while a person was standing in a free field 20 m from the explosion then that person might experience eardrum damage. However, if that person was sheltered from the overpressure by being behind a building at the time of the hazard, then the overpressure received by that person could be insufficient to cause eardrum damage.

The probability of occurrence of a UVCE is not very high since the probability of major tank failure is 8.76×10^{-5} failures/year for spontaneous tank failure and 4.38×10^{-4} failures/year for failure resulting from impact. The peak overpressure, which occurs at the source of the explosion, is 33.3 kPa at both 30°C and -10°C. This overpressure is insufficient in magnitude to cause death directly since the overpressure needed to cause 50% mortality is 140 kPa. However, the overpressure is sufficient to cause 50% structural damage to buildings when situated 48 m and 35 m from the source at 30°C and -10°C, respectively.

9.2.2 BLEVE

The separation distances at which specified damage from a BLEVE could occur are listed in Table 10. Figures 5 and 6 are a graphical representation of these results and Figure 7 illustrates the overpressure contours at which specified damage could occur.

If a BLEVE occurred at 30°C, the peak overpressure would be sufficient to cause 50% mortality within 2 m from the tank. Although, this distance may seem insignificant, it is not. This would be of significance if a vehicle was to collide with the storage tank while the station attendant was filling an automobile with propane, the attendant would probably be within 2 m from the tank at the time of collision. The risk of 50% mortality from a BLEVE to an individual standing 2 m from the tank is 5.26×10^{-5}/year at 30°C ; reduced probability of death exists at distances greater than 2 m.

The peak overpressure at -10°C is insufficient to cause death because the tank pressure is reduced at the lower temperature. However, there is a 50% probability of a person receiving eardrum damage if that person is situated within 3 m from the tank at the time of the BLEVE.

9.2.3 Fireball

The limiting separation distances to avoid the incident radiation from a fireball are listed in Table 11. The consequences of thermal radiation from a fireball are also listed in Table 12. Figure 8 shows the thermal radiation separation contours at which specified thermal radiation can be avoided.

In the event of a BLEVE there is the possibility of a fireball being associated with it. The consequence from a fireball is that of thermal radiation. The separation distances listed are distances at which a person can avoid the specified incident thermal radiation.

The effect that ambient temperature has on the separation distances for thermal radiation is clearly evident. For example, at 30°C, the distance at which an incident flux of 4.7 kW/m² occurs is 112 m, whereas, at -10°C, this distance is only 86 m. If a person was sheltered from the incident thermal radiation by being behind a building at the time of the fireball, then the aforementioned distance would be reduced. The amount of reduction of incident thermal radiation depends on the size and material of construction of the shielding object. For example, if a person was sitting in a car at the time of the fireball then that person would receive a different level of thermal flux than a person located inside of a building the same distance away.

The calculations for the thermal radiation hazards from the propane fireball were performed at both zero and 50% relative humidity. From Table 11, it can be seen that the separation distances are not strongly dependent upon relative humidity. For example, the safety separation distance for an incident thermal radiation of 12.6 kW/m²

(30°C) at zero relative humidity is 69 m and 64 m at 50% relative humidity. The difference in these two values is approximately 7%. At -10°C the difference between the two relative humidities is reduced to only 1.5%. Since the effect of relative humidity is negligible with respect to the accuracy of the models, the worst case scenario, i.e. zero relative humidity, has been assumed for the rest of the thermal radiation calculations.

The risk of 50% mortality from a fireball when situated 23 m from the source at 30°C or situated 17 m from the source at -10°C is 2.63×10^{-5}/year. These risks are based on a period of exposure which is equal to that of the duration of the fireball. The duration of the fireball is 4.4 s and 3.7 s at 30°C and -10°C, respectively.

9.2.4 Tank Fire

The limiting separation distances required to avoid the specified incident thermal radiation from a tank fire in a no wind situation are listed in Table 13 and those for wind of 2 m/s are listed in Table 14. The consequences of incident thermal radiation from a tank fire for the no-wind situation and for a wind speed of 2 m/s are listed in Tables 15 and 16, respectively.

The wind speed of 2 m/s was chosen to be representative of an actual wind condition. However, in built-up area, the wind is rarely at a constant speed nor is it predominantly from one direction. Since structures such as buildings on either side of a road form tunnels through which the wind will travel, minor obstructions, such as trees, mailboxes, or automobiles, will cause turbulent eddies to form in the air-flow. The result is a wind which fluctuates continuously in both speed and direction. For this reason the separation distances listed could fluctuate in magnitude depending on the wind behaviour at the time of the hazard. Again, the distances listed are for a free field, and not for a built-up area as in the core of large urban centres.

It was found that the separation distances for the wind and no-wind scenarios differ. The separation distance for a thermal flux of 4.7 kW/m² is 89 m for the no-wind situation and 94 m for a wind speed of 2 m/s, at an ambient temperature of 30°C. The flame length is also increased with an increase in wind velocity. The effects of flame lengthening and the consequent bending toward the ground combine to increase the values of safety separation distances in the direction of the flame tilt with an increase in wind velocity.

The effects of ambient temperature on the separation distances is also apparent from the results obtained. At 30°C the limiting distance at which a radiation flux of 4.7 kW/m² occurs is 89 m and is 86 m at -10°C. This difference arises from the effect of temperature on the vapour pressure of propane and on combustion effects.

Another factor that must be explained is that of duration of exposure for the individual to the incident thermal radiation. The greater the time of exposure the greater the total thermal radiation dose received by the target. A person exposed to a high level of

thermal flux for a short period of time could receive the same dose as a person exposed to lower level of flux over a longer period of time. The effects of duration of exposure will depend on the state of the individual, age, fitness, general health and proximity to the thermal source. These factors would also determine the time required for the individual to obtain shelter from the thermal radiation. Obviously, infants and old or handicapped persons would not be able to reach shelter from thermal radiation as quickly as a young,healthy person. Therefore, the duration of exposure would be longer for infants and old or handicapped persons than for the young and healthy [1]. These two different scenarios were considered in this study. Two different exposure durations producing the same dose were considered. The exposure times used to simulate these two scenarios were 60 s as the exposure time for infants and for old or handicapped persons and 15 s for a young healthy person.

The distance from the source at which 50% mortality would occur was determined for both scenarios. The results showed that the risk for 50% mortality from a tank fire was 2.19×10^{-4}/year when situated at 29 m from the source for a 15 s exposure duration or when situated 49 m from the source for a 60 s exposure. This particular example is based on an ambient temperature of 30°C and at a wind velocity of zero. The magnitude of these values diminishes with decrease in temperature and increases with increase in wind speed. The risks for other cases are listed in Table 48.

9.2.5 Pool Fire

The safety separation distances from a pool fire are listed in Tables 17 and 18. The thermal radiation consequences for a pool fire are listed in Tables 19 and 20.

If a two-phase release of propane occurred then the liquid portion of the release would immediately begin to flash after contact with the ground. This endothermic flashing process would then begin to cool the ground, thus decreasing the rate of flashing from the liquid pool. If the two-phase release of the propane is of sufficient magnitude to cool the ground to -42.1°C, then the pool of liquid would cease to flash, and remain as a liquid pool for sufficient time to form a pool fire. An unbunded release would, in all likelihood, evaporate and not form a pool fire. Nonetheless, if the release was partially bunded, by a road kerb for example, then the probability of obtaining a pool fire would increase.

The actual size of an unbunded pool is not known with certainty. Therefore, two representative sizes have been chosen for purposes of calculation in order to illustrate the thermal consequences from a pool fire. The two sizes chosen were a 2 m and a 5 m pool diameter. At a specified distance the consequences of the incident thermal radiation are greater for the larger pool than for the smaller pool. For example, the separation distance from the centre of a 5 m pool at which a risk of 2.19×10^{-3}/year for 50% mortality occurs is 69 m and is 31 m for a 2 m pool, for a 15 s exposure at 30°C for both pools.

9.2.6 Premixed Flash Fire

The release of propane from a failed component, e.g. broken valve stem, will result in the formation of a turbulent jet which will entrain air and thereby form a well-mixed flammable cloud. The size of the pre-mixed cloud formed will depend on the following:

(i) proximity and size of neighbouring structures
(ii) local wind speed and direction
(iii) local induced turbulence
(iv) delay time prior to ignition

All four of these factors will affect the rate of dispersion of the propane vapour cloud and thereby determine the size of flammable cloud available for the flash fire. Since these four effects vary with meteorological conditions and at each particular station, prediction of the extent of their effects is difficult. As a result, only the maximum flammable cloud size for pre-mixed flash fire for the free-field situation can be determined.

The maximum flammable cloud radius for a pre-mixed flash fire are listed in Table 21 for various discharge diameters. For a 2.53×10^{-3} m diameter discharge orifice the maximum flammable cloud radius is 15 m at 30°C and 11 m at -10°C. As the discharge orifice increases in diameter the maximum size of the cloud also increases.

9.2.7 Jet Fire

The limiting separation distances to avoid the specified thermal radiation from a jet fire are listed in Tables 22 and 23. The thermal radiation consequences from a jet fire are also listed in Tables 24 and 25. Figure 11 shows the thermal radiation contours from a 0.0381 m diameter of jet fire.

The different diameters of jet fires listed in Table 1 are representative of the size of failures that could result in the formation of a jet fire. It was found that the flame length increases with an increase in jet diameter. As the flame length increases, the radiation intensity also increases. This means that the larger the flame, the greater the limiting separation distance from the source for a specified incident thermal radiation. Furthermore, the effect of temperature on the intensity of incident thermal radiation is similar to that for a tank fire.

There is a 5.01×10^{-2} m (2 in.) diameter pressure relief valve situated on the top of the storage tank. There is a possibility of actuating this pressure releif valve if the storage tank was overpressurized. An event resulting in such a consequence could occur if the tanker truck overfilled the storage tank. If this was the case then overpressurization of the tank would cause the relief valve to open thereby expelling propane into the atmosphere. If this expelled propane was ignited, a jet fire could form. The length of the jet flame would be 11.3 m and would produce an incident flux of 4.7 kW/m^2 at a distance of 91 m from the jet flame at 30°C.

Both the barbecue cylinder dipsenser nozzle and the autombile dispenser nozzle are fitted with an excess flow valve. The primary purpose of an excess flow valve is to protect against excessive flow when breakage or rupture of the hose takes place. The term breakage or rupture refers to a clean and complete separation. If the damage is only a crack or if the hose is crushed at the point of failure, the escaping flow will be restricted and may or may not pass sufficient vapour or liquid to cause the excess flow valve to close.

The excess flow valve, while in its normal open position, permits the flow of liquid or gas in either direction. Flow is controlled in one direction only. If the flow exceeds a predetermined rate the valve automatically closes. In general the excess flow valve closes at approximately 50% greater flow than the anticipated normal flow. This is important since valves with a closing flow very close to the normal flow may chatter or slug closed when surges in the line occur either during normal operation or due to the rapid opening of a control valve. Excess flow valves should be tested at periodic intervals.

The separation distances required from a possible jet flame from either the barbecue or automobile dispenser hoses when the flow is 50% greater then the normal flow are less in magnitude than the separation distances required if the excess flow valve failed open or if the line rupture occurred upstrem from the excess flow valve. For example, the safety separation distance required to avoid an incident flux of 4.7 kW/m^2, at 30°C, is 14 m for the former case and only 70 m for the latter. The reason for this difference is that the exit velocity in the failed situation is much greater than that when the exit stream velocity is only 50% greater than the normal flow.

The probability of equipment failure, such as a leaking valve, with a resulting jet fire is greater than that of major tank failure. This is evident from Tables 6 and 7. However, the magnitude of the consequences of a jet fire would not be as great as a UVCE or a BLEVE. As in the case of the tank fire both 15 s and 60 s exposure durations were considered.

9.2.8 Confined Explosion

If the ignition of a vapour cloud from a release of propane was delayed then the cloud would disperse. The cloud might disperse sufficiently to render it non-flammable. In general, when establishing a criterion level for the non-flammability of an unconfined mixture, the concern is that of the average concentration of the mixture. As a result, 50% LFL is often chosen as this criterion level. Therefore, in this study a non-flammable unconfined cloud is defined as a cloud that has a peak concentration below 50% LFL.

There are several reasons why 50% LFL is chosen as a criterion for safety for unconfined mixtures; amongst these reasons are:

(i) apparatus-dependence of limits of flammability
(ii) effects of pressure and temperature on the LFL
(iii) influence of magnitude of the source of ignition
(iv) effect of turbulence in the dispersing flow
(v) uncertainty in the form and location in a real atmosphere of concentration isopleths predicted by models of dispersion

In order for a confined explosion to occur, a flammable mixture must be in a confined volume, such as a building, and subsequently be ignited. When dealing with confined clouds, the concern is that of a specific concentration level, since the cloud is assumed to be homogeneously mixed. Subsequently, the criterion level for the non-flammability of a confined mixture is the LFL. If ignition of the vapour cloud from the release of propane is delayed, so that the mixture results from dispersion either by dilution to less than the LFL before confinement or by dilution of a richer mixture to less than the LFL in confinement, the threat of explosion is removed.

The distances listed in Table 26 are the distances that the propane cloud must travel in order for its peak concentration to drop to the LFL in a 2 m/s wind.

9.2.9 Asphyxiation

The separation distances to avoid asphyxiation from a major release of propane from the propane storage tank are listed in Table 27. These values will be modified appreciably by both the proximity of nearby structures and by local patterns of airflow.

The limiting separation distance from the source needed to avoid asphyxiation from a major propane release at 30°C is 15 m and 11 m at -10°C, with a wind speed of 2 m/s. The higher temperature causes the release of a greater amount of propane. The height of the cloud is 5.0 m at 15 m from the source (at 30°C) and 3.6 m at 11 m from the source (at -10°C). Both of these cloud heights are well above the height of any human being and, therefore, asphyxiation is a reality for anybody standing within these specified separation distances.

9.2.10 Overfilling Automobile Propane Tank

It is common practice when fueling a car to put a few more squirts of fuel in the tank to 'round' the payment up to the nearest dollar. If this took place when filling a propane tank, then local asphyxiation could be a hazard to the station attendant. Every automobile propane tank has a bleeder valve located on the top of the tank designed to expel into the atmosphere any extra propane put into the tank. This extra propane released into the atmosphere could be an asphyxiation hazard for the person filling the tank.

The distance required to disperse this extra propane to the the point where it is no longer an asphyxiation hazard is 0.5 m and 0.3 m at 30°C and -10°C, respectively, for a wind velocity of 2 m/s (Table 28). Although these distances are small, they must be taken into account since the person filling the propane tank is in extremely close proximity to the point of release from the bleeder valve. However, these distances are insufficient in magnitude to prevent easy escape by the attendant from the asphyxiant hazard. Upon smelling a propane release from the bleeder valve, the attendant must only take one step back from the automobile to avoid asphyxiation. Diminished olfactory powers and accommodations may deleteriously affect this situation.

9.3 Gasoline

For purposes of comparison the safety separation from the hazards associated with a gasoline storage tank were also evaluated. The hazards considered for a gasoline tank storage were: tank fire, pool fire, jet flame and confined explosions.

Since the composition of gasoline varies significantly, hexane was chosen as a representative compound for gasoline.

9.3.1 Tank Fire

The limiting separation distances to avoid the specified thermal radiation from a gasoline tank fire are listed in Table 29. The thermal radiation consequences from a gasoline tank fire are listed in Table 30.

Gasoline tanks are usually sited below ground, while propane tanks are usually above ground. It has already been stated that the likelihood of catastrophic failure of a propane tank is low. This is true for gasoline tanks, but the probability of failure is lower in that the intervention of a purpose-directed force is required to propagate the failure, e.g. an excavator in close proximity. However, another feature of these tanks is that the propane tank is a pressure vessel and therefore strong, whereas gasoline tanks are atmospheric tanks and are built to withstand only the hydrostatic head.

The availability of gasoline to the fire is likely to be lower because of the limited size of breach. In-ground tanks are prone to corrode and, as a result, gasoline might be released. 'Ground-fires' are less hazardous than pool fires, although somewhat more difficult to deal with.

The separation distances from a gasoline tank fire are greater than that for an equivalent–sized propane tank fire. For example, the limiting distance to a thermal flux of 4.7 kW/m^2 at 30°C is 115 m for a gasoline tank fire and 89 m for that of a propane tank fire. Similarly, the consequences of a gasoline tank fire are greater than those for an equivalent-sized propane tank fire. For example, for an equal risk of 2.19 x 10^{-2}/year for

50% mortality, the separation distance for a tank fire is 31 m and for a similar propane tank fire the separation distance is 29 m, both at 30°C and a 15 s exposure. However, this difference of 2 m is insignificant and therefore, it can be said that the magnitude of consequences from a gasoline tank fire are equivalent to that of propane tank fire.

9.3.2 Pool Fire

The limiting safety separation distances to avoid the specified incident thermal radiation from a gasoline pool fire are listed in Tables 31 and 32. The thermal radiation consequences from a gasoline pool fire are listed in Tables 33 and 34.

Since gasoline, unlike propane, is a liquid at room temperature, it will not flash when exposed to the atmosphere. Instead it will form a liquid pool on the ground much more readily than will propane, although it is unlikely that the gasoline will be bunded. Therefore, the size of the pool fire that might be formed is unknown. However, it is more likely for a gasoline pool fire to occur than a propane pool fire. Gasoline, however, evaporates into the atmosphere at a rate which is dependent upon the ambient temperature.

It is possible for the pool to become semi-confined if partially bunded by a road side kerb. For purposes of comparison, the pool sizes used in the calculations of separation distances were assumed to be the same as propane, i.e. the two diameters of pool sizes chosen were 2 m and 5 m.

The results obtained for the safety separation distances from a gasoline pool fire were very similar in magnitude to those obtained for a propane pool fire. This trend is consistent with that obtained for tank fires in the previous section.

9.3.3 Jet Fire

The limiting separation distances necessary to avoid the specified thermal radiation intensity from a gasoline jet fire are listed in Tables 35 and 36. The thermal radiation consequences from a gasoline jet fire are listed in Tables 37 and 38.

When gasoline is pumped into an automobile it is not pumped into pressurized containment as is propane. Therefore, the rate of release from a breach in a gasoline line or pump would be less in magnitude than that of a similar propane leak. Therefore, the size of the jet flame of the two-phase mixture formed from a gasoline leak would be smaller than a propane jet flame. As a result, the thermal radiation from a gasoline jet fire would be less hazardous than that from a similar propane fire. The results obtained for the safety separation distances from a gasoline jet fire confirm this argument. For example, the limiting distance for 50% mortality is 22 m for a propane jet fire and only 5 m for a similar gasoline jet fire. This example is for a 15 s exposure to a 3.81×10^{-2} m jet orifice at 30°C. This trend is consistent for the entire range of jet fire diameters analyzed.

9.3.4 Confined Explosion

The separation distances from the point of release at which the concentration level in a gasoline vapour cloud is at the LFL are listed in Tables 39 and 40.

Calculations were based on the evaporation rate of gasoline from 2 m and 5 m diameter gasoline pools. The results showed that the rate of evaporation from such a pool is sufficient to form a flammable gasoline cloud with effects of thermal radiation at large distances from the cloud. For example, the distance from which a gasoline vapour cloud must travel to be rendered non-flammable (i.e LFL) is 30 m for a 5 m diameter pool and 20 m for a 2 m pool at 30°C. At -10°C these distances decrease as expected. If the liquid pool was released onto an impermeable, sloped surface then the liquid could travel into a confined space, such as a building. Depending on the quantity of liquid available and the volume of the confined space, a flammable mixture would be formed. If this flammable mixture was ignited then a confined explosion would result. For mixtures of similar stoichiometric composition for both propane and gasoline, the explosion pressures generated will be similar. They will range for a completely filled building from 7 – 8 times the initial pressure (i.e. ambient).

9.4 Propane Tank Truck

There is the possibility that a release of containment could occur when the large tank truck is on site to refuel the propane storage tank. If a major storage tank failure was to occur while the tank truck was on site, then any missiles produced from the storage tank failure could penetrate the neighbouring tank truck. This would result in major failure of the tank truck. Obviously, the probability of occurrence of such an event is small since the tank truck is on site only a few times per week depending on the tank size and rate of turnover.

Another, possible incident leading to major failure of both the storage tank and the propane tank truck could result from collision of the tank truck with the storage tank. The probability of this occurring is also small since the tank truck is mobile at the station site for approximately two minutes per visit. However, the possibility of major failure still exists. If such a failure were to occur then the quantity or inventory of propane released would be dramatically increased. The capacity of a typical tank truck is approximately 60 000 L. Therefore, the resultant consequences from hazards involving the tank truck would be greater than those of the storage tank alone.

9.4.1 UVCE

The safety separation distances from a UVCE involving the tank truck are listed in Table 41.

The extent of overpressure from a UVCE with the increased inventory is much greater than that for the storage tank alone. For example, the limiting distance for 10% window breakage is increased from 1350 m to 2570 m for the increased inventory at 30°C. As expected the temperature trends are consistent with earlier findings.

Although the separation distances at which specified damage would occur are greater for the case of increased inventory, the results must be considered in the light of the probability of occurrence of such an event. The risk of 50% mortality at 64 m from the source of the explosion is only 1.31×10^{-6}/year at 30°C.

9.4.2 BLEVE

The separation distances for which specified damage due to overpressure would occur from a BLEVE involving tank truck are listed in Table 42.

Again, as expected, the magnitude of the separation distances from a BLEVE involving a tank truck are much greater than those obtained for the storage tank situation. For example, the safety separation distances for 10% window breakage is increased from 240 m to 313 m at 30°C for the tank truck situation. However, the probability of such an occurrence is much lower than in the case of the storage tank. The risk for 50% mortality from a BLEVE involving a tank truck is 1.58×10^{-7}/year at 8 m from the source at 30°C.

9.4.3 Fireball

The safety separation distance to avoid the specified incident thermal radiation from a fireball resulting from a tank truck BLEVE is listed in Table 43. The thermal radiation consequences from the fireball are listed in Table 44.

The results are again consistent with those obtained for a UVCE and BLEVE. For example, the distance at which a thermal flux of 4.7 kW/m² can be avoided is increased from 112 m to 188 m for the tank truck situation at 30°C. The temperature trends are consistent with those obtained previously. For a 50% mortality risk of 7.90×10^{-8}/year the limiting separation distance for the tank truck situation is 47 m at 30°C as compared to a distance of 23 m and a risk of 2.63×10^{-5}/year for the storage tank situation also at 30° C.

9.4.4 Pool Fire

The safety separation distances required to avoid the specified incident thermal radiation from a tank truck pool fire are listed in Table 45. The thermal radiation consequences for the tank truck pool fire are listed in Table 46.

Again it is unlikely that an unconfined pool fire would form. However, the probability of a tank truck pool fire is greater than that of the storage tank situation simply because the tank truck can release approximately 3.5 times the amount of the propane than the storage tank. Since the actual size of pool fire formed is not known, a representative size

of, say, 10 m in diameter has been chosen for calculation purposes. It was found that for a 10 m pool fire the limiting separation distance for a flux of 4.7 kW/m² is 379 m at 30°C and 369 m at -10°C. The safety separation distance for a thermal consequence of 50% mortality for a 15 s exposure duration is 124 m at 30°C and 121 m at -10°C. The risk associated with this consequence is 1.31×10^{-5}/year.

9.4.5 Asphyxiation

The separation distances necessary to avoid asphyxiation from a major tank truck release are listed in Table 47.

The distance to avoid asphyxiation from the tank truck release is 26 m at 30°C and 19 m at -10°C. Again, as expected, these distances are much greater than those for the storage tank release. The height of the cloud is 7.8 m at 26 m from the source (at 30°C) and 5.4 m at 19 m from the source (at -10°C). Both of these cloud heights are well above the height of any human being and, therefore, asphyxiation is a reality for anybody standing within these specified separation distances.

9.5 Regulation Distances

The minimum separation distances as outlined in the Propane Code [16] are listed below:

	Minimum Distance in Metres Between a Tank and		
Tank Capacity (USWG)	Property Line, Adjacent Concrete or Masonry Building Wall with No Openings Within the Specified Clearance, Source of Ignition	Building Wall of Other than Concrete or than Concrete or Masonry Construction	Building Opening
2000 to 5000	5	7.5	7.5

In general the safety separation distances calculated in this report are greater than those suggested in the Propane Code [16].

In order to give validity to the values of safety separation distances, the corresponding risk present at that specified distance should also be determined. The corresponding risks associated with the report's calculated separation distances were determined and are listed in this report. By examining the associated risks, the safety separation distances can be classified as being reasonable or unreasonable in light of the

corresponding level of risk. However, in order to do this the level of acceptable risk must be determined and/or selected. The selection of an acceptable risk level is no easy task. There are many factors which must be considered in selecting the level of acceptable risk. These include:

(i) population density in vicinity of hazard
(ii) accessibility of emergency services to hazard site
(iii) evacuation ability of general public
(iv) proximity of public buildings, e.g. schools
(v) proximity of commercial buildings, e.g. shops

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Conclusions

(1) The hazards from propane leaking from storage tanks have been examined and quantified. These hazards are:

(i) UVCE
(ii) BLEVE
(iii) Fireball
(iv) Tank Fire
(v) Premixed Flash Fire
(vi) Jet Flame
(vii) Confined Explosion
(viii) Asphyxiation

(2) Of the hazards listed in (1), only (iv), (vi) and (vii) exist for gasoline. In addition, gasoline may produce a pool fire.

(3) The risk to an individual from propane is greater than for gasoline in two respects.

(i) for propane, the same level of risk occurs, but further removed from the storage tank than for gasoline
(ii) as shown in (1) and (2), there are more hazard scenarios for propane than for gasoline

(4) The individual risk of death from a BLEVE, of the storage tank, without a fireball, on the basis of 50% mortality, is 5.26×10^{-5} per annum.

(5) The individual risk of death from a BLEVE of a tanker truck on site, without a fireball, on the basis of 50% mortality, is 1.58×10^{-7} per annum.

(6) There are measurable risks of asphyxiation from propane releases that are greater than those from gasoline. This is due in part to release of gas stored under pressure and in part to the fact that the effects of leaks of gasoline are localised.

(7) While escape has not been considered in this report, leakage of gasoline is generally more visibly obvious than that of propane. Thereby, earlier warning is imparted and greater opportunity exists for escape. However, to provide some warning of release, propane distributed for fuel purposes has a distinctive odorant content sufficient to ensure that it is readily detectable in the atmosphere down to concentrations of 20% of the lower flammable limit of propane.

(8) It may be concluded that while high standards of engineering operation and maintenance care are required in the supply of gasoline, higher standards and more stringent operation, planning and regulation are required for propane.

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Recommendations

(1) In view of the distances presented relating to death and injury arising from releases of propane, there seems to be a clear call for greater separation from buildings and particularly residences. However, this is directly dependent upon the level of acceptable risk. To assist in this consideration, values of 'every-day' risks are listed below.

Event (U.S. 1968-1973)	Individual Risk of Death to those exposed to the event (per annum)
Tornado	2.35×10^{-7}
Electrocution	5.00×10^{-6}
Fire and Flames	3.60×10^{-5}
Accidental Falls	8.50×10^{-5}
Motor Vehicles	2.70×10^{-4}
All Accidents	5.50×10^{-4}
Motor Vehicle –Train Collision	7.40×10^{-3}

Selected risks associated with the propane storage tank are listed below (from Table 48):

Event (Propane Storage Tank)	Individual Risk of 50% Mortality to those exposed to the event (per annum)
BLEVE	5.26×10^{-5}
Fireball	2.63×10^{-5}
Tank Fire	2.19×10^{-4}
Jet Fire	2.19×10^{-2}

(2) The report indicates that there are grounds for setting minimum separation distances in the range of 20 to 40 m. Whereas, the Propane Installation Code [16] suggests minimum separation distances in the range of 5 m to 7.5 m. While it is

necessary to consider these safety separation distances, attention should also be directed to any forms of enclosure, eg. huts, containers, garages, that may be erected albeit temporarily, within this distance. Thereby, the probability of confined explosions would be reduced.

(3) In view of the fact that large vehicles have to manoeuvre in close proximity to the storage tanks, more effective barriers than some of those presently installed are required. Considerations regarding these barriers should include:

(i) reduction in spacing distance between posts
(ii) increase post height above grade (to at least lift-off height of back of tanker truck)
(iii) specifying minimum thickness of post steel
(iv) increase diameter of posts
(v) installed posts should completely circumscribe the installation, i.e. both storage tank and dispenser
(vi) implementation of kerbing around the entire installation
(vii) investigating the use of other types of posts, e.g. I-beams

(4) The resistance of storage tanks and tank trucks to impinging flames and to high levels of thermal radiation could be improved by application of intumescent coatings(*), as is done in the petro-chemical industry.

(5) Investigation of the efficacy and applicability of fixed fire protection equipment, e.g. fixed spray nozzles for the storage tank should be undertaken.

(6) Improve the reliability of the installation by increasing the frequency of inspection, testing and maintenace of the components. The probability of failure may be reduced, e.g. decrease the fractional dead-time of controls. Since all equipment is liable to failure and eventually fails, using equipment of superior quality and construction will result in a reduction in the probability of component failure because such equipment possesses a lower failure rate.

Another method of increasing reliability is by installing redundant equipment. Thus, double valving may be appropriate. These considerations should be brought to bear upon those parts of the installation that are considered to be most critical.

(7) Dispenser hoses are vulnerable by reason of accident and misuse. There seem to be several approaches to reducing this vulnerability:

(i) restricting the length of hoses and, possibly, to a length of less than twice the distance between the dispenser and the barrier
(ii) use of retractable hoses

(*) Top quality enamel paint: $0.10/sq.ft. of area painted.
Top quality intumescent paint: $4.50 /sq.ft. of area painted

(iii) installing devices to ensure that the valve and filling connection do not trail on the ground
(iv) review the type of valving used for refuelling
(v) the use of break-away couplings and and non-return valves should be reviewed and the advantages of redundancy investigated

(8) Active steps should be taken to reduce the number of sources of ignition (e.g. rubberising the metal propane dispenser nozzles as are many of the gasoline dispenser nozzles). Sources of ignition are ubiquituous and the number can only be reduced. However, it has to be recognised that sources of ignition extend beyond flames and smoking materials and include electrics (static and power), impact, friction, etc.

(9) Analysis of the optimum basis of safe and economic operation of propane refueling involves:

(i) frequency of replenishment of storage tank
(ii) size of storage tank
(iii) frequency and consequence of a BLEVE from the storage tank and from the tank truck

The present report does not address this point but provides a basis for their consideration.

In this context, it may be that restricted routing of tankers and optimum times of delivery should also be considered.

(10) Training of all personnel involved should be reviewed; topics should include:

(i) safe operation
(ii) properties and behaviour of propane
(iii) contingency planning
(iv) familiarisation exercises with the fire fighting service
(v) vehicle movements, particularly related to the refuelling tank truck

(11) In view of the fact that propane can produce more severe consequences than gasoline, the risk of which has been accepted, more detailed analysis and planning and stricter controls, as outlined in (1) through (10), are required. If this is not done, propane, a valuable and attractive fuel, will be placed at a disadvantage.

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Appendix I: Calculations

All of these calculations were performed at 30°C and -10°C.

Unconfined Vapour Cloud Explosion (UVCE)

At 30°C

Determination of the amount of propane vapour originally in tank:

Total volume of tank (V_{Tank}): 18 927 L

Assume tank filled to 85% capacity:

Therefore, volume of liquid in propane tank when filled to 85% capacity is:

0.85 x 18 927 L = 16 088 L

Total moles of liquid propane (n_T) in tank is:

$$n_T = (V_T \cdot \rho_l)/M, \quad (1)$$

where,

V_T: total volume of liquid propane
ρ_l: density of propane liquid
M: molecular weight of propane

Therefore,

$V_T = 16.088\ m^3$
$\rho_l = 487 \times 103\ g/m^3$
$M = 44.11\ g/mol$

Therefore,

$n_T = 177\,621$ mol

Now, use the ideal gas law to determine what fraction of n_T is in the vapour phase:

Therefore,

$$n_g = \frac{P \cdot V}{Z \cdot R \cdot T} \quad (2)$$

where,

n_g: moles of propane in vapour phase
P: vapour pressure of propane
V: volume of tank occupied by propane vapour
Z: compressibility factor
R: gas constant
T: ambient temperature

Therefore,

$P = 1\,054\,600$ Pa
$V = V_{Tank} - V_l$, (m^3)
$Z = 0.84$
$R = 8.314$ J/mol · K
$T = 303$ K

where,

V_{Tank}: total volume of tank
V_l: volume of liquid propane in equilibrium with vapour

where,

$$V_l = n_l \cdot V_{spec}, \tag{3}$$

where,

n_l: moles of propane in liquid phase
V_{spec}: specific volume of liquid propane

where,

$V_{spec} = 9.05 \times 10^{-5}$ m^3/mol

$$n_l = n_T - n_g, \tag{4}$$

therefore,

$$V_l = 9.05 \times 10^{-5} (n_T - n_g), \tag{5}$$

Substitution into (2),

therefore,

$n_g = 1\,557.23$ mol

and,

n_l = 176 063.76 mol

Also,

V_l = 15 946.97 L

and,

V_g = 141.03 L

where, V_g is the volume of propane vapour that is in equilibrium with propane liquid.

Note: V_g is in terms of liquid not gas.

similarly,

At -10°C,

V_l = 16 087.61 L

and,

V_g = 0.48 L

Now determine the amount of vapour that would flash-off if the tank failed catastrophically:

At 30°C

Using, (Canvey [13]):

$$m_v = 1 - \exp\{(-S/L) \cdot [T_s - T_b]\}, \quad (6)$$

where,

m_v: mass fraction vapourized
S: specific heat of liquid
L: latent heat of liquid
T_s: storage temperature of liquid
T_b: boiling point of liquid stored

therefore,

S = 2 616.8 J/kg·°C
L = 330 756 J/kg
T_s = 30°C

T_b = -42.1°C

therefore,

m_v = 0.435

Therefore, volume of liquid flash (V_f):

$V_f = (0.435 \times V_l)$

therefore,

V_f = 6 936.93 L

At -10°C

m_v = 0.175

and therefore,

V_f = 2 815.32 L

Therefore total amount of vapour released (V_r):

$$V_r = V_f + V_g, \qquad (7)$$

At 30°C

V_r = 6 936.93 L + 141.03 L
V_r = 7 077.96 L

similarly,

At -10°C

V_r = 2 816.79 L

Therefore,

	30°C	-10°C
Total mass of propane released (kg):	3,446.97	1,529.52
Total volume of propane released (m^3):		
liquid as liquid:	7.08	2.82
vapour as vapour:	1,944.14	748.66

Determination of the flammable vapour cloud size formed upon release of the propane:

According to Clancey[6], for hydrocarbons that have a ratio of upper to lower flammability limits in the range of four to six, two thirds of the total release is available for combustion.

Since flammability ratio of propane is approximately five:

therefore,

$$V_{FL} = (2/3) \cdot V_t , \tag{8}$$

where,

V_t: total volume of propane gas released
V_{FL}: volume of propane gas in flammable envelope

therefore,

At 30°C

since,

$V_t = 1994.14\ m^3$

therefore,

$V_{FL} = 1296.09\ m^3$

similarly,

At -10°C

$V_t = 748.66\ m^3$

therefore,

$V_{FL} = 499.11\ m^3$

Using Wiekema's model[26], the cloud is assumed to be hemispherical with homogeneous stoichiometric concentration throughout.

First, determine the stoichiometric concentration of the cloud:

$$C_3H_8 + 5O_2 \rightarrow 4H_2O + 3CO_2 , \tag{9}$$

since,

$C_3H_8:O_2 :: 1:5$

Now, assume 100 moles of air, therefore,

21 moles of O_2 and

79 moles of N_2 required.

Therefore,

$\frac{21}{5}$ = 4.2 moles of C_3H_8 required.

Therefore, stoichiometric volume fraction of C_3H_8 in air is:

$$\frac{4.2}{21 + 79 + 4.2} = 0.04031 \text{ or } 4.031\%$$

Since,

At 30°C

$V_{FL} = 1296.09\ m^3$

therefore, the stoichiometric amount of air in the flammable cloud, V_a, is:

$$\frac{4.031}{(100 - 4.031)} = \frac{1296.09}{V_a}, \qquad (10)$$

therefore,

$V_a = 30\,856.97\ m^3$

similarly,

At -10°C

$V_{FL} = 499.11\ m^3$

therefore, the stoichiometric amount of air in the flammable envelope, V_a, is:

$$\frac{4.031}{(100 - 4.031)} = \frac{499.11}{V_a}, \qquad (11)$$

therefore,

$$V_s = 11\,882.68\ m^3$$

Therefore, the total volume of the flammable cloud, V_s, is:

$$V_s = V_{FL} + V_{ox}, \tag{12}$$

therefore,

At 30°C

$$V_s = 32\,153.09\ m^3$$

similarly,

At -10°C

$$V_s = 12\,381.73\ m^3$$

Now determine the radius (r_o) of this cloud:

Using,

$$V_s = 0.5\,[(4/3) \times (3.14) \times (r_o)^3], \tag{13}$$

therefore,

At 30°C

$$r_o = 24.8\ m$$

and

At -10°C

$$r_o = 18.1\ m$$

Now, determine the overpressure as a result of deflagration (Wiekema[26]).

$$L = [(2/3) \cdot (3.14) \cdot (r_o)^3 \cdot (E_C / P_o)]^{(1/3)}, \tag{14}$$

where,

- L: characteristic explosion length
- r_o: radius of hemispherical cloud before combustion
- E_C: available combustion energy for a stoichiometric mixture
- P_o: atmospheric pressure

Note: only 20% of the available combustion energy, (E_c), is used for the shock wave formation.

therefore,

At 30°C

r_o = 24.8 m
E_c = 3.5 x 10^6 J/m^3
P_o = 101 325 Pa

therefore,

L = 60.43 m

If r_1 is the radius of the hemispherical cloud after combustion and the assumed average velocity is 160 m/s, then:

$r_1/L = 0.456$, (Wiekema[26]) (15)

hence,

r_1 = 27.6 m

similarly,

At -10°C

r_o = 18.1 m
E_c = 3.5 x 10^6 J/m^3
P_o = 101 325 Pa

therefore,

L = 44.10 m

and,

r_1 = 20.1 m

According to Wiekema[26], when the radius of the cloud, r is equal to r_1 the overpressure is at its maximum (i.e. peak overpressure occurs at $r = r_1$).

The attenuation of overpressure outside the cloud (i.e. for $r = r_1$ to $r \rightarrow \infty$)

$PS = 1.5 \times 10^{-1} (L/r)$, (Wiekema[26]) (16)

where,

PS: is the dimensionless overpressure
i.e. $PS = (P - P_o)/P_o$, (17)

where,

P: overpressure (+ atmospheric pressure)
P_o: atmospheric pressure

i.e.

$P - P_o$ = effective overpressure

From equation (16), the dimensionless overpressure (i.e. when $r = r_1$),

At 30°C

PS = 0.329

therefore,

P = 134.661 kPa,

for a flame velocity of 160 m/s.

Due to the form of Wiekema's model [26] and the assumptions made therein, the dimensionless overpressure at -10°c is also 0.329.

Figures 2 and 3 represent plots of the effective overpressure ($P - P_o$) from the blast wave versus the distance from the centre of the cloud at 30°C and -10°C, respectively.

The equation of the line in Figures 2 and 3 was derived from equation (16) according to the following:

$PS = 1.5 \times 10^{-3} \cdot (L/r)$, (16)

therefore, combining (16) and (17),

$P - P_o = P_o(1.5 \times 10^{-3}) \cdot (L/r)$, (18)

The actual values plotted in Figures 2 and 3 are listed in Appendix II (Obtained through equation (18)).

The positive phase duration of the explosion, (i.e. when r expands from r_o to r_1), follows the following equation (Wiekema[26]):

$$t = r_1 [(1/v_n) - (1/C_o)] + [(3A/7) \cdot (L/C_o) \cdot \ln \frac{[1 + ((7/3A) \cdot (r/L))]}{[1 + ((7/3A) \cdot (r_1/L))]}, \quad (19)$$

where,

- t: positive phase duration
- v_{FL}: average flame velocity
- C_o: speed of sound
- A: constant (dependent on average flame velocity)
- L: characteristic explosion length
- r: distance from cloud centre at any time
- r_1: radius of cloud after combustion

therefore,

At 30°C

v_{FL} = 160 m/s
C_o = 330 m/s
A = 1.5 x 10^{-1}
L = 60.43 m
r_1 = 27.6 m

therefore,

positive duration (s)	distance from cloud centre, r (m)
0.089	27.6
0.103	100
0.130	1000
0.135	1500

and

At -10°C

v_{FL} = 160 m/s
C_o = 330 m/s
A = 1.5 x 10^{-1}
L = 44.10 m
r_1 = 20.1 m

therefore,

positive duration (s)	distance from cloud centre, r (m)
0.065	20.1
0.078	100
0.097	1000

Boiling Liquid Expanding Vapour Explosion (BLEVE)

The calculations performed for the BLEVE were based on the work done by Gaydon and Hurle [10].

Calculation of shock front pressure due to a BLEVE:

Therefore,

$$\frac{P_4}{P_1} = \frac{2 \cdot \gamma_1 \cdot (M_1)^2 - (\gamma_1 - 1)}{(\gamma_1 + 1)} \times$$

$$[1 - [(\gamma_4 - 1)/(\gamma_1 + 1)] \cdot [a_1/a_4] \cdot [M_1 - (1/M_1)]^{-\frac{2\gamma_4}{(\gamma_4 - 1)}} \quad (20)$$

where,

P_1: atmospheric pressure
P_4: pressure inside tank
γ_1: ratio of heat capacities of air
γ_4: ratio of heat capacities of propane
a_1: relative speed of sound in air
a_4: relative speed of sound in liquid propane
M_1: mach number

therefore,

At 30°C

P_1 = 101.325 kPa
P_4 = 1054.600 kPa
γ_1 = 1.40
γ_4 = 1.127
a_1 = 0.345 km/s
a_4 = 0.354 km/s

therefore, solving for M_1, by iteration, in equation (20):

M_1 = 1.605

and

At -10°C

$P_1 = 101.325$ kPa
$P_4 = 348.800$ kPa
$\gamma_1 = 1.40$
$\gamma_4 = 1.140$
$a_1 = 0.345$ km/s
$a_4 = 0.234$ km/s

therefore,

$M_1 = 1.272$

Using,

$$M_1 = w_s/a_1 , \tag{21}$$

where,

w_s: speed of the shock front

therefore,

At 30°C

$w_s = 0.553$ km/s

and

At -10°C

$w_s = 0.439$ km/s

Now calculate the pressure of the shock front using:

$$\frac{P_2}{P_1} = \frac{(2 \cdot \gamma_{ave} \cdot (M_1)^2) - (\gamma_{ave} - 1)}{(\gamma_{ave} + 1)}, \tag{22}$$

where,

P_2: pressure of the shock front
γ_{ave}: average of the two heat capacity ratios

that is:

$$\gamma_{ave} = \frac{(\gamma_1 + \gamma_4)}{2} , \tag{23}$$

At 30°C

$$P_2 = 279.637 \text{ kPa}$$

and

At -10°C

$$P_2 = 171.390 \text{ kPa}.$$

In order to calculate the effect of the blast wave, the following should be assumed:

1) the blast wave travels radially in all directions from the tank
2) the pressure decreases with distance according to the following equation (Baker et al. [22])

$$\log (PS) = -1.118 \log (R) + c , \tag{24}$$

where,

PS: dimensionless overpressure
R: dimensionless distance
c: constant

where,

$$R = \frac{r}{[V[(P_4/P_1) - 1] / [\gamma_4 - 1]]^{(1/3)}} , \tag{25}$$

where,

r: distance from tank
V: volume of tank
P_4: pressure inside tank
P_1: atmospheric pressure
γ_4: ratio of heat capacities of propane

since,

$$V = \frac{(3.14) \times d^2 \times h}{4}, \tag{26}$$

$d = 1.83$ m
$h = 7.33$ m

therefore,

$$V = 19.27\ m^3$$

Therefore,

At 30°C

from equation (25).

$$r = 11.26R\ , \tag{27}$$

and,

At -10°C

$$r = 6.95R\ , \tag{28}$$

Now, calculate the distance from the centre of the tank, r_o, at which the peak overpressure, P_2, exists:

therefore,

$$R_o = \frac{1}{\{4.189 \times [((P_4/P_1) - 1)/\gamma_4]\}^{(1/3)}}, \tag{29}$$

where

R_o: dimensionless distance at which P_2 exists

therefore,

At 30°C

$$R_o = 0.15$$

and from equation (28),

$$r_o = 1.69\ m$$

also,

At -10°C

$$R_o = 0.24$$

and from equation (29),

$$r_o = 1.67\ m$$

Now, using r_o and P_2 as initial conditions, the value for the constant, c, can be calculated.

Recall equation (24),

$$\log (PS) = -1.118 \log (R) + c$$

now, to solve for c, let;

$$PS = PS_2 \text{ and } R = R_o,$$

where,

PS_2: dimensionless peak overpressure

where,

$$PS_2 = (P_2 - P_o)/P_o , \tag{30}$$

where,

P_2: peak overpressure of shock front
P_o: atmospheric pressure

therefore,

At 30°C

$$PS_2 = 1.76$$

and, therefore,

$$c = -0.676$$

also,

At -10°C

$$PS_2 = 0.69$$

and, therefore,

$$c = -0.854$$

Therefore, the dimensionless overpressure as a function of dimensionless distance is described by the following equations:

At 30°C

$$\log (PS) = -1.118 \log (R) - 0.676 , \tag{31}$$

and,

At -10°C

$$\log (PS) = -1.118 \log (R) - 0.854 , \quad (32)$$

Figures 5 and 6 show plots of effective overpressure, P, as a function of the actual distance from the tank centre, r, for 30°C and -10°C, respectively. These plots are based on equations (31) and (32) respectively.

The plotted points for Figures 5 and 6 are listed in Appendix II.

Fireball

There may be a Fireball associated with the BLEVE.

Determination of the effects of a fireball:

Using, (Wells [25])

$$D = 3.9(W^{0.33}) , \quad (33)$$

and,

$$t = 0.3(W^{0.33}) , \quad (34)$$

where,

D:	diameter of fireball
W:	weight of propane in fireball
t:	duration of fireball

Therefore,

At 30°C

Assuming that all of the propane in the vapour phase is active in the fireball.

$$W = 3446.97 \text{ kg}$$

therefore,

$$D = 57.33 \text{ m}$$

and,

$$t = 4.41 \text{ s}$$

At -10°C

$$W = 1529.52 \text{ kg}$$

therefore,

$$D = 43.85 \text{ m}$$

and,

$$t = 3.73 \text{ s}$$

Now determine the distance from the fireball at which specified intensities exist:

$$I = E \cdot \sigma \cdot T^4 \cdot n^{-2} \cdot \cos(a) , \tag{35}$$

where,

I: intensity of radiation at the receiver
E: emissivity
σ: Stefan Boltzmann constant
T: temperature of fireball

$$n: \frac{\text{distance from centre of fireball, } d_f}{\text{radius of fireball}} , \tag{36}$$

a: angle of elevation to a vertical receiver,(human)

therefore,

At 30°C

$E = 0.5$
$\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$
$T = 1273 \text{ K } (1000°C)$
$n = d_f / (57.3/2)$
$a = 15°$

therefore,

$$d_f = [(59\,090\,048.74) / I]^{0.5} \text{ m} , \tag{37}$$

and,

At -10°C

$$d_f = [(34\,569\,226.33) / I]^{0.5} \text{ m} , \tag{38}$$

The following is a list of distances from the centre of the fireball at which the specified intensities exist:

Radiation Intensity (kW/m^2)	Distance From Fireball (-10°C) (m)	(30°C) (m)
4.7	85.76	112.13
12.6	52.38	68.48
37.8	30.24	39.54

The following is a list of distances from the centre of the fireball at which the specified effects occur:

Effects	Distance From Fireball (-10°C) (m)	(30°C) (m)
First Degree Burns	43.3	56.8
Ignition of Buildings	35.3	46.4

Note: duration of exposure is the actual duration of the fireball.

Tank Fires

After the flashing release of some of the pressurized propane from the storage, the remaining propane will be in the liquid state at its boiling point (-42.1°C). This liquid remaining in the tank could be ignited to form a tank fire.

In order to determine the thermal radiation from a tank fire certain basic aspects of the fire system must first be determined. These are: burning rate, flame length correlations and flame tilt correlations.

Burning Rate:

Using Burgess and Zabetakis [9]:

$$m'' = m_{inf} \cdot (1 - \exp(-k \cdot b \cdot D)) , \qquad (39)$$

where,

- m'': mass burning rate
- m_{inf}: infinite mass burning rate
- k: extinction coefficient
- b: mean beam length corrector
- D: tank diameter

and,

$$m_{inf} = 1 \times 10^{-3} (H_c / (H_v)^*) , \tag{40}$$

where,

H_c: heat of combustion
$(H_v)^*$: modified heat of vaporization

and,

$$(H_v)^* = H_v + \int_{T_o}^{T_b} C_p(T)\, dT , \tag{41}$$

where,

H_v: heat of vaporization at the boiling point
T_b: normal boiling point of fuel
T_o: ambient temperature
$C_p(T)$: specific heat of liquid fuel

where,

$$C_p(T) = a_1 + b_1 T + c_1 T^2 + d_1 T^3 , \tag{42}$$

where,

a_1, b_1, c_1, and d_1: constants

Therefore,

$k = 2.7/m$
$b = 1$
$D = 1.8288$ m
$H_c = 5.0340 \times 10^7$ J/kg
$H_v = 4.28 \times 10^5$ J/kg
$T_b = -42.1$°C
$a_1 = -1.009$
$b_1 = 7.315 \times 10^{-2}$
$c_1 = -3.789 \times 10^{-5}$
$d_1 = 7.678 \times 10^{-9}$

therefore,

At 30°C

$(Hv)^* = 453\,390$ J/kg

and,

$m_{inf} = 0.111$ kg/m$^2 \cdot$ s

and therefore,

$m'' = 0.111$ kg/m$^2 \cdot$ s

At -10 °C

$(H_v)^* = 434\,687$ J/kg

and,

$m_{inf} = 0.116$ kg/m$^2 \cdot$ s

and therefore,

$m'' = 0.116$ kg/m$^2 \cdot$ s

Flame Length Correlation:

Using (Thomas [22]):

$$L = 42D \cdot (m'' / (\rho_o \cdot [g \cdot D]^{0.5}))^{0.61}, \qquad (43)$$

where,

L:	mean flame length
D:	tank diameter
ρ_o:	ambient air density
m":	mass burning rate
g:	gravitational constant

Therefore,

At 30 °C

$D = 1.8288$ m
$\rho_o = 1.166$ kg/m^3
$m'' = 0.111$ kg/m$^2 \cdot$ s
$g = 9.81$ m/s^2

therefore,

$L = 7.585$ m

similarly,

At -10°C

$$L = 7.148 \text{ m}$$

Equation (43) applies to still-air conditions.

For situations where a steady wind is blowing, Thomas[25] has given:

$$L = 55D \cdot \{m^* / (\rho_a \cdot [g \cdot D]^{0.5})\}^{0.67} \cdot (U_*)^{0.21}, \quad (44)$$

where,

U_*: dimensionless wind velocity

and,

$$U_* = (U/U_c), \quad (45)$$

where,

U: wind velocity
U_c: characteristic wind velocity

and,

$$U_c = (g \cdot m^* \cdot D / \rho_a)^{1/3}, \quad (46)$$

Assume Class F Pasquill Weather Stability Category [17]:

That is:

$$U = 2 \text{ m/s}$$

Therefore,

At 30°C

$$U_c = 1.195 \text{ m/s}$$

therefore,

$$U_* = 1.674$$

and, therefore,

$$L = 8.814 \text{ m}$$

and,

At -10°C

$$U_c = 1.157 \text{ m/s}$$

therefore,

$$U_* = 1.729$$

and, therefore,

$$L = 8.314 \text{ m}$$

Flame Tilt Correlation:

Using Welker and Sliepcevich [20]:

therefore,

$$\frac{\tan(a)}{\cos(a)} = 3.3\, Re^{0.07}\, Fr^{0.8}\, (\rho_g/\rho_o)^{-0.6}, \qquad (47)$$

where,

a:	deflection of flame from the vertical (flame tilt)
Re:	Reynolds Number
Fr:	Froude Number
ρ_g:	density of fuel vapour at normal boiling point
ρ_o:	ambient air density

where,

$$Re = (D \cdot U \cdot \rho_o / u), \qquad (48)$$

and,

$$Fr = (U^2 / D \cdot g), \qquad (49)$$

where,

D:	tank diameter
U:	wind velocity
ρ_o:	ambient air density
u:	viscosity of ambient air
g:	gravitational constant

where,

$\rho_g = 2.327$ kg/m^3
$D = 1.8288$ m
$U = 2$ m/s
$g = 9.81$ m/s^2

therefore,

At 30°C

$\rho_a = 1.166$ kg/m^3
$u = 1.86 \times 10^{-5}$ kg/m · s

therefore,

$Re = 2.293 \times 10^5$

and,

$Fr = 0.894$

and, therefore,

$a = 36°$

also,

At -10°C

$\rho_a = 1.343$ kg/m^3
$u = 1.67 \times 10^{-5}$ kg/m · s

therefore,

$Re = 2.941 \times 10^5$

and,

$Fr = 0.991$

and, therefore,

$a = 38°$

The distance at which a particular level of thermal radiation exists, can now be determined.

Therefore, using the Stefan-Boltzmann equation:

$$q_r = F \cdot A_f \cdot \tau \cdot \varepsilon \cdot \sigma \cdot [(T_f)^4 - (T_o)^4] , \quad (50)$$

where,

- q_r: intensity of thermal radiation
- F: viewfactor, i.e. the fraction of radiation leaving the flame that is incident upon the target
- A_f: area of the flame 'seen' by the target
- τ: atmospheric transmissivity
- ε: flame emissivity
- σ: Stefan-Boltzmann constant
- T_f: flame temperature
- T_o: ambient temperature

also,

$$e = 1 - \exp(-kD) , \quad (51)$$

where,

- k: extinction coefficient
- D: diameter of tank

View Factors:

When wind velocity equals zero (Stannard [19]):

$$F = (2/3.14) \cdot \sin^{-1}(D/2x) \cdot \sin[\tan^{-1}(L/[x - (D/2)])] , \quad (52)$$

where,

- D: diameter of tank
- L: mean flame length
- x: distance from source centre to target

When wind velocity is not equal to zero (Stannard [19]):

$$F = (2/3.14) \cdot \sin^{-1}\{(D/2)/[(D/2)+(x - (D/2)) \cdot \cos(a)]\} \times \{[\sin(a) + \sin[\tan^{-1}((L^{**}/(x - (D/2) \cdot \cos(a))) - \tan(a))]] - \{\sin(a) + \sin[\tan^{-1}((L^{*}/(x - (D/2) \cdot \cos(a))) - \tan(a))]\} \quad (53)$$

where,

- D: tank diameter
- x: distance from source centre to target
- a: deflection of flame from the vertical (flame tilt)
- L^{**}: corrected flame length (for tank height and wind)
- L^{*}: corrected flame length (for tank height only)

Although tank fires are subject to fluctuations from both wind and turbulence, they are usually of sufficient duration to be considered as attaining a steady state. Therefore, intensities of thermal radiation from such flames can be predicted for the purposes of determining separation distances.

For wind velocity equal to zero and using equation (50):

At 30°C

where,

$A_f = 13.871\ m^2$
$\tau = 1$
$\varepsilon = 1$
$\sigma = 5.676 \times 10^{-11}\ kW/m^2 \cdot K^4$
$T_f = 1273\ K$
$T_o = 303\ K$
$q_r = 2060.95(F)$, (54)

By substituting equation (52) into equation (54) and solving for, x, by iteration, for the three radiation intensities of concern, the following results were obtained:

Radiation Intensity (kW/m^2)	Distance from Source Centre to Target (m)
4.7	89
12.6	55
37.8	32

Similarly, using equation (50):

At -10°C

where,

$A_f = 13.072\ m^2$
$\tau = 1$
$\varepsilon = 1$
$\sigma = 5.676 \times 10^{-11}\ kW/m^2 \cdot K^4$
$T_f = 1273\ K$
$T_o = 263\ K$
$q_r = 1944.94(F)$, (55)

By substituting equation (52) into equation (55) and solving for, x, by iteration, for the three radiation intensities of concern, the following results were obtained:

Radiation Intensity (kW/m^2)	Distance from Source Centre to Target (m)
4.7	86
12.6	53
37.8	31

For wind velocity not equal to zero (i.e a wind velocity of 2 m/s) using equation (50)

At 30°C

where,

$A_f = 9.475\ m^2$
$\tau = 1$
$\varepsilon = 1$
$\sigma = 5.676 \times 10^{-11}\ kW/m^2 \cdot K^4$
$T_f = 1273\ K$
$T_o = 303\ K$

where,

$a = 36°$
$L^{**} = 17.87\ m$
$L^{*} = 9.06\ m$

$$q_r = 1407.80(F), \qquad (56)$$

By substituting equation (53) into equation (56) and solving for, x, by iteration, for the three radiation intensities of concern, the following results were obtained:

Radiation Intensity (kW/m^2)	Distance from Source Centre to Target (m)
4.7	90
12.6	58
37.8	36

Similarly, using equation (50):

At -10°C

where,

$Af = 9.362\ m^2$
$\tau = 1$
$\varepsilon = 1$
$\sigma = 5.676 \times 10^{-11}\ kW/m^2 \cdot K^4$
$T_f = 1273\ K$
$T_o = 263\ K$

and where,

$a = 38°$
$L^{**} = 17.62\ m$
$L^{*} = 9.30\ m$

$$q_r = 1392.64(F)\ , \qquad (57)$$

By substituting equation (53) into equation (57) and solving for, x, by iteration, for the three radiation intensities of concern, the following results were obtained:

Radiation Intensity (kW/m^2)	Distance from Source Centre to Target (m)
4.7	87
12.6	55
37.8	34

Pool Fire

If liquid propane was released into an unbunded area a pool might form depending on the magnitude of the release. The size of the pool formed would not be known; therefore, two representative pool diameters were arbitrarily chosen. The diameters of the two sizes considered are 2 m and 5 m.

The analysis for determining thermal radiation effects from a pool fire are nearly identical to that used for a tank fire, except that the view factor for a pool fire is different than that for a tank fire. The view factor is different because the base of a pool is situated on the ground, whereas, the base of a tank fire is situated at the liquid level of the tank.

Therefore, using results from equations (39) to (42):

At 30°C

$m'' = 0.111$ kg/m²s

and,

At -10°C

$m'' = 0.116$ kg/m²s

and using equation (43):

(wind = 0 m/s)

then,

At 30°C

for pool diameter = 2 m

$L = 8.07$ m

and,

for pool diameter = 5 m

$L = 15.26$ m

At -10°C

for pool diameter = 2 m

$L = 7.86$ m

and,

for pool diameter = 5 m

$L = 14.38$ m

Using equations (50) to (52):

for Pool Diameter = 2 m

Radiation Intensity (kW/m^2)	Distance From Source Centre to Target (m) 30°C	-10°C
4.7	97	95
12.6	59	58
37.8	34	34

and,

for Pool Diameter = 5 m

Radiation Intensity (kW/m^2)	Distance From Source Centre to Target (m) 30°C	-10°C
4.7	211	205
12.6	129	125
37.8	75	72

Flash Fire

Presently there is very little modelling information on flash fires. However, the quantity of the material involved in a flash fire can be determined on the basis of the rate of release of flammable material.

Pre-mixed Flash Fire

To determine the size of the propane cloud available for a pre-mixed flash fire, the distance from the source at which the concentration of the cloud is at 50% LFL must be calculated.

The Sutton ([20, 21]) model will be used for this calculation.

For a continuous point source at ground level, the concentration at the centre, X_{cc}, can be expressed as:

$$X_{cc} = (2 \cdot m) / (3.14 \cdot C^2 \cdot u \cdot x^{2-n}) , \qquad (58)$$

where,

m: continuous mass release rate
C: diffusion parameter
u: wind velocity
x: distance from source to cloud centre
n: diffusion index

The next step is to determine the continuous mass release rate of propane from a breach in the storage tank:

First, determine the composition of flashing flow from the tank:

$$P_c = (2/(\gamma+1))^{\gamma/(\gamma+1)} \times P_1 , \qquad (59)$$

where,

P_c: choke pressure
γ: ratio of the specific heats of propane gas
P_1: pressure in the tank

and

At 30°C

$\gamma = 1.127$
$P_1 = 1\,054\,600$ Pa

therefore,

$P_c = 610\,687$ Pa

Now, the choke temperature can be determined: the choke temperature, T_c, is defined as that temperature at which the vapour pressure is P_c

therefore,

$T_c = 280$ K

and,

At -10°C

$\gamma = 1.140$
$P_1 = 348\,800$ Pa

therefore,

$P_c = 201\,052$ Pa
$T_c = 247$ K

Now, determine the gas fraction from

$$m_v = 1 - \exp\left[(-S/L) \cdot [T_s - T_c]\right], \tag{60}$$

where,

m_v: mass fraction vapourized
S: specific heat of liquid
L: latent heat of liquid
T_s: storage temperature of liquid
T_c: choke temperature of mixture

and

At 30°C

$S = 2616.8$ J/kg·°C
$L = 330\,756$ J/kg
$T_s = 30$°C
$T_c = 7$°C
$m_v = 0.166$

similarly,

At -10°C

$m_v = 0.092$

Next, determine the density of the two-phase mixture at the choke form

$$\rho_c = m_v \cdot \rho_v + m_l \cdot \rho_l, \tag{61}$$

where,

ρ_c: two-phase mixture density at the choke
m_v: mass fraction vapourized
ρ_v: density of vapour
m_l: mass fraction not vapourized

i.e. $m_l = 1 - m_v$, (62)

ρ_l: density of liquid

At 30°C

$m_v = 0.166$
$\rho_v = 1.773$ kg/m^3
$m_l = 0.834$
$\rho_l = 487$ kg/m^3

whence,

$\rho_c = 406.5$ kg/m^3

and,

At -10°C

$m_v = 0.092$
$\rho_v = 2.043$ kg/m^3
$m_l = 0.908$
$\rho_l = 543$ kg/m^3

whence,

$\rho_c = 493.3$ kg/m^3

The mass discharge rate may be determined from

$$m = k \cdot A \cdot [2 \cdot \rho_c (P_1 - P_c)]^{0.5}, \quad (63)$$

where,

m: mass discharge rate
k: discharge coefficient
A: area of discharge
ρ_c: two-phase mixture density at the choke
P_1: pressure in tank
P_c: choke pressure

thus,

At 30°C

where,

$k = 0.8$
$\rho_c = 406.5\ kg/m^3$
$P_1 = 1\,054\,600\ Pa$
$P_c = 610\,687\ Pa$
$m = 15\,197.9 \times A\ (kg/s)$, (64)

for an area of discharge, A. (N.B. the units of A are m^2).

Thus, inserting the following into equation (58):

$X_{\alpha z} = 0.018615\ kg/m^3$ (50% LFL)
$C = 0.21$
$u = 2\ m/s$
$n = 0.25$

distances to 50% LFL are obtained as under.

Diameter of Discharge Area (m)	Distance From Source to Cloud Centre (50% LFL) (m)
2.53×10^{-3}	15
1.91×10^{-2}	154
2.83×10^{-2}	242

similarly,

At -10°C

$k = 0.8$
$\rho_c = 493.3\ kg/m^3$
$P_1 = 348\,800\ Pa$
$P_c = 201\,052\ Pa$
$m = 9\,658.8 \times A\ (kg/s)$, (65)

for an arbitrary area of discharge, A.(At -10°C)

and,

X_{cc} = 0.02145 kg/m³ (50% LFL)
C = 0.21
u = 2 m/s
n = 0.25

thus, relevant values for distances to 50% LFL are:

Diameter of Discharge Area (m)	Distance From Source to Cloud Centre (50 % LFL) (m)
2.53×10^{-3}	11
1.91×10^{-2}	110
2.83×10^{-2}	172

Note: These distances quantify the size of the flammable region.

Asphyxiation

Propane is classified as a simple asphyxiant, which means that in the event of a release, the propane would displace the oxygen necessary for survival.

The minimum level of oxygen in the atmosphere necessary for survival is 6%.

Determination of the amount of propane required in the atmosphere to produce 6% oxygen:

Air: 21% oxygen
79% nitrogen

therefore,

$O_2:N_2$ :: 1:3.762

for 6% oxygen,

amount of propane = 100 - [(3.762x6) + 6] = 71.428%

Therefore,

$$\rho_{mix} = (0.7143 \times \rho_g) + ([1 - 0.7143] \times \rho_o) , \quad (66)$$

where,

ρ_{mix}: density of air with 6% oxygen
ρ_g: density of propane
ρ_o: density of air with 21% oxygen

therefore,

At 30°C

$\rho_g = 1.773$ kg/m³
$\rho_o = 1.166$ kg/m³

and, therefore,

$\rho_{mix} = 1.600$ kg/m³

similarly,

At -10°C

$\rho_g = 2.043$ kg/m³
$\rho_o = 1.343$ kg/m³

therefore,

$\rho_{mix} = 1.843$ kg/m³

determine the size of the asphyxiant cloud:

assume: cloud size is proportional to storage tank dimensions

tank dimensions: radius = 0.9144 m
height = 7.33 m

At 30°C

volume of propane release into initial cloud, V_o:

$V_o = 1944.14$ m³

dimensions of initial cloud (pure propane):

radius, $r_o = 4.4$ m
height, $h_o = 35.3$ m

assume: homogeneous mixture in cloud

volume of propane cloud with 6% oxygen, V_f:

$$V_f = V_o \cdot (\rho_g / \rho_{mix}) , \quad (67)$$

where,

ρ_g: density of propane
ρ_{mix}: density of propane with 6% oxygen

therefore, using equation (67),

$V_f = 2154.35\ m^3$

similarly,

At -10°C

$V_o = 748.66\ m^3$
$r_o = 3.2\ m$
$h_o = 25.7\ m$

therefore,

$V_f = 829.90\ m^3$

Determine the radius of the cloud, r, and the height of the cloud, h, with 6% oxygen (Van Ulden [27]):

therefore,

$$r = r_o (V_f / V_o)^{(1/2a)} , \quad (68)$$

where,

r: radius of cloud with 6% oxygen
r_o: initial radius of cloud
V_f: radius of cloud at r
V_o: initial volume of cloud
a: constant

and,

$$h = h_o (r / r_o)^{(2a-2)} , \quad (69)$$

where,

h: height of cloud with 6% oxygen

At 30°C

r_o = 4.4 m
V_r = 2154.35 m³
V_o = 1944.14 m³
a = 0.1

therefore, using equation (68),

r = 12.3 m

and, using equation (69),

h = 5.0 m

similarly,

At -10°C

r_o = 3.2 m
V_r = 829.90 m³
V_o = 748.66 m³
a = 0.1

therefore,

r = 9.0 m

and,

h = 3.6 m

Determine the time required, t, for the cloud to expand from r_o to r (Van Ulden [27]):

therefore,

$$t = \frac{r^3 - (r_o)^3}{2c \cdot [[g \cdot (\rho_o - \rho_a) \cdot V_o]/3.14 \cdot \rho_a]^{0.5}}, \quad (70)$$

where,

r: radius of cloud
r_o: initial radius of cloud
c: constant
g: gravitational constant
ρ_o: density of gas
ρ_a: density of air
V_o: initial volume of cloud

therefore,

At 30°C

$r = 12.3$ m
$r_o = 4.4$ m
$c = 1$
$g = 9.81$ m/s²
$\rho_o = 1.773$ kg/m³
$\rho_a = 1.166$ kg/m³
$V_o = 1944.14$ m³

therefore,

$t = 1.5$ s

and, therefore, the distance the cloud has travelled, d, in time t for a 2 m/s wind is:

$d = 3$ m

therefore, the separation distance, d_s, from a propane release to avoid asphyxiation is (r + d):

$d_s = 15.3$ m

similarly,

At -10°C

$r = 9.0$ m
$r_o = 3.6$ m
$c = 1$
$g = 9.81$ m/s²
$\rho_o = 2.043$ kg/m³
$\rho_a = 1.343$ kg/m³
$V_o = 748.66$ m³

therefore,

$t = 1.2$ s

and, therefore, the distance the cloud has travelled, d, in time t for a 2 m/s wind is:

$d = 2.4$ m

therefore, the separation distance, d_s, from a propane release to avoid asphyxiation is (r + d):

$d_s = 11.4$ m

Confined Explosions

It is also important to determine the distance travelled by the cloud to render it non-flammable. This will provide one with a separation distance between the source and a building in which a confined explosion could take place.

Using, (Van Ulden [27]):

$$u_f = (c/r) \cdot [g \cdot (\rho_o - \rho_a) \cdot V_o] / [3.14 \cdot \rho_o]^{0.5}, \quad (71)$$

where,

u_f:	frontal velocity of the cloud
c:	constant
r:	radius of cloud
g:	gravitational constant
ρ_o:	density of gas
ρ_a:	density of air
V_o:	initial volume of cloud

calculate the radius, r, and the height, h, of the cloud where (Van Ulden [27]):

$$u_f = 2u^*, \quad (72)$$

where,

u^*: friction velocity

therefore,

At 30°C

$u^* = 0.5$ m/s
$c = 1$
$g = 9.81$ m/s
$\rho_o = 1.773$ kg/m^3
$\rho_a = 1.166$ kg/m^3
$V_o = 1944.14$ m^3

therefore,

$r = 91.2$ m

and, using equation (69),

$h = 0.11$ m

similarly,

At -10°C

$u^* = 0.5$ m/s
$c = 1$
$g = 9.81$ m/s
$\rho_o = 2.043$ kg/m^3
$\rho_a = 1.343$ kg/m^3
$V_o = 748.66$ m^3

therefore,

$r = 56.6$ m

and, using equation (69),

$h = 0.11$ m

determine the time required, t, for the cloud to expand from r_o to r (using equation (70)):

therefore,

At 30°C

$t = 91$ s

and, therefore, the distance the cloud has travelled, d, in time t for a 2 m/s wind is:

$d = 182$ m

similarly,

At -10°C

$t = 57$ s

and, therefore, the distance the cloud has travelled, d, in time t for a 2 m/s wind is:

$d = 114$ m

Now, use Clancey [6] to determine the distance the cloud must travel (from distance d) to render the cloud non-flammable:

therefore,

$$\sigma_m = \{2 \cdot Q^* / [(2x3.14)^{(3/2)} \cdot X_{cc}]\}^{1/3}, \qquad (73)$$

where,

σ_m: standard deviation of concentration distribution when cloud is at maximum potential
Q^*: quantity of propane in initial release
X_{cc}: concentration at centre of cloud

Assume:

- a wind speed of 2 m/s

initially:

- concentration at the centre of the cloud is pure propane
- concentration at the edge of the cloud is at the lower flammability limit (LFL)

therefore,

At 30°C

$Q^* = 3\,446.97$ kg
$X_{cc} = 1.773$ kg/m^3

therefore,

$\sigma_m = 6.27$ m

similarly,

At -10°C

$Q^* = 1\,529.52$ kg
$X_{cc} = 2.043$ kg/m^3

therefore,

$\sigma_m = 4.56$ m

Also, (Clancey [67])

$$r = \{2 \cdot (\sigma_m)^2 \cdot \ln(X_{cc} / X_b)\}^{0.5}, \quad (74)$$

where,

r: radius of flammable cloud
X_b: concentration at edge of cloud

therefore,

At 30°C

$\sigma_m = 6.27$ m
$X_{cc} = 1.773$ kg/m^3
$X_b = 0.03723$ kg/m^3

therefore,

$r = 17.4$ m

similarly,

At -10°C

$\sigma_m = 4.56$ m
$X_{cc} = 2.043$ kg/m^3
$X_b = 0.04290$ kg/m^3

therefore,

$r = 12.7$ m

Now, determine the volume, V, of the cloud with radius, r and height, h:

therefore,

$$V = (3.14) \cdot r^2 \cdot h, \tag{75}$$

At 30°C

where,

$r = 12.7$ m
$h = 0.11$ m

therefore,

$V = 104.6$ m^3

and,

At -10°C

where,

$r = 12.7$ m
$h = 0.11$ m

therefore,

$$V = 55.7\ m^3$$

Now, use Sutton [20] to determine the distance travelled by the cloud to render it non-flammable:

therefore,

$$X_{cc} = \frac{2 \cdot Q^{**}}{(3.14)^{(3/2)} \cdot C^3 \cdot (ut)^{(3/2) \times (2-n)}}, \qquad (76)$$

where,

X_{cc}:	concentration at centre of cloud (LFL)
Q^{**}:	quantity of propane in flammable cloud
C:	constant
ut:	distance of cloud travel (to render it non-flammable)
n:	constant

where,

$$Q^{**} = V \cdot (\rho_g + \rho_{LFL}] / 2), \qquad (77)$$

where,

ρ_g:	density of pure propane
ρ_{LFL}:	density of mixture at LFL

therefore,

At 30°C

$$\rho_g = 1.773\ kg/m^3$$
$$\rho_{LFL} = 0.03723\ kg/m^3$$

therefore,

$$Q^{**} = 94.7\ kg$$

similarly,

At -10°C

$$\rho_g = 2.043\ kg/m^3$$
$$\rho_{LFL} = 0.04290\ kg/m^3$$

therefore,

$Q^{**} = 58.1$ kg

therefore,

At 30°C

$X_{cc} = 0.03723$ kg/m^3
$Q^{**} = 94.7$ kg
$C = 0.21$
$n = 0.25$

therefore,

$(ut) = 79.9$ m

similarly,

At -10°C

$X_{cc} = 0.04290$ kg/m^3
$Q^{**} = 58.1$ kg
$C = 0.21$
$n = 0.25$

therefore,

$(ut) = 62.8$ m

Therefore, the total distance travelled by cloud, d_t, until it is rendered non-flammable is:

$$d_t = d + ut, \tag{78}$$

therefore,

At 30°C

$d_t = 182$ m + 79.9 m
$d_t = 261.9$ m

similarly,

At -10°C

$d_t = 114$ m + 62.8 m
$d_t = 176.8$ m

Jet Flames

Jet flames result from ignition of a high pressure gaseous discharge of a compressed flammable liquid. The visible flame length of the jet can be predicted by using the following equation (Raj [10]):

$$\frac{L}{d_j} = (5.3/C_T) \cdot \{ [T_F/w_T \cdot T_o] \cdot [C_T+(1-C_T) \cdot (M_o/M_j)] \}^{0.5}, \quad (79)$$

- L: visible flame length
- d_j: diameter of jet
- T_F: effective flame temperature
- w_T: ratio of reactants to products in unreacted stoichiometric mixture
- T_o: ambient air temperature
- C_T: jet fluid mole fraction in unreacted stoichiometric mixture
- M_o: molecular weight of air
- M_j: molecular weight of jet fluid at exit

If the average flowrate at the exit port exceeds Mach 0.2 then lift-off occurs. This would would result in the flame burning at a distance, a, from the exit port. Kent [10] has developed the following equation for calculation of the lift-off distance:

$$a = 1.6\ (3.14)\ d_j\ (u_o/u_i)\ , \quad (80)$$

where,

- a: lift-off distance
- u_o: sonic velocity
- u_i: velocity of jet at Mach 0.2

First, determine if lift-off occurs;

Recall equations (64) and (65):

(Mass discharge rate, $\dot{m}$, as a function of discharge area, A)

Note: A is in m^2.

At 30°C

$$\dot{m} = 15\ 197.9 \times A\ (kg/s)\ , \quad (64)$$

and

At -10°C

$$\dot{m} = 9\,658.8 \times A \text{ (kg/s)}, \tag{65}$$

Therefore,

$$u_c = \dot{m} / (A \cdot \rho_c), \tag{81}$$

where,

u_c: linear velocity at the choke
ρ_c: two-phase mixture density at the choke

At 30°C

where,

$\rho_c = 406.5$ kg/m3

and, therefore,

$u_c = 37.38$ m/s

and

At -10°C

where,

$\rho_c = 493.3$ kg/m^3

and, therefore,

$u_c = 19.58$ m/s

Now, determine the exit velocity using the Bernoulli equation:

$$u = \{[2(P_c - P_o)/\rho_{ave}] + (u_c)^2\}^{0.5}, \tag{82}$$

where,

u: exit velocity of jet
P_c: choke pressure
P_o: atmospheric pressure

$$\rho_{ave} = (\rho_u + \rho_c) / 2, \tag{83}$$

and,

ρ_{ave}: average density
ρ_u: density at the upper flammability limit
ρ_c: two-phase mixture density at the choke

At 30°C

where,

P_c = 610 687 Pa
P_o = 101 325 Pa
ρ_u = 1.227 kg/m³
ρ_c = 406.5 kg/m³

therefore,

ρ_{ave} = 203.86 kg/m³

and, therefore,

u = 79.97 m/s

At -10°C

where,

P_c = 201 052 Pa
P_o = 101 325 Pa
ρ_u = 1.414 kg/m³
ρ_c = 493.3 kg/m³
ρ_{ave} = 247.22 kg/m³

and, therefore,

u = 34.50 m/s

Recall equation (80) for determining lift-off:

$$u_l / u_o > 0.2 , \tag{84}$$

where,

$u_l = u$

therefore,

At 30°C

u_o = 267 m/s

therefore,

u_l/u_o = 0.30

therefore, lift-off occurs at 30°C

$$a = 25.13\, d_j, \tag{85}$$

Note: d_j is in metres

also,

At -10°C

u_o = 248 m/s

therefore,

u_l/u_o = 0.14

therefore, lift-off does not occur at -10°C.

The length of the visible jet flame can be determined using equation (79)

therefore,

At 30°C

w_T = 0.96
T_o = 303 K
C_T = 0.0403
M_o = 29 g/mol
M_j = 44.11 g/mol

therefore,

$$L = 225.41 \times d_j, \tag{86}$$

At -10°C

w_T = 0.96
T_o = 263 K
C_T = 0.0403
M_o = 29 g/mol
M_j = 44.11 g/mol

therefore,

$$L = 241.94 \times d_j \ , \tag{87}$$

Now, determine the radiation effects of the jet flame using a Linear Multi Point Source Model (Crocker and Napier [89]):

Assume:

- target is vertical
- target is one metre in height
- flame source normal is perpendicular to target
- flame source is at ground level

then,

$$q = \frac{f \cdot Q \cdot x}{6.28L \cdot (4ac-b^2)} \{ ([2az_2 + b] / P_2) + ([2az_1 + b] / P_1) \} \ , \tag{88}$$

where,

q:	radiation flux at target
f:	fraction of total heat released as radiation
Q:	total heat released by combustion
x:	target position from jet centre line
L:	visible flame length
z_1:	height of flame source above ground
z_2:	height of flame above ground

and where,

$a = 1$
$b = -2z$
$c = x^2 + y^2 + z^2$
$P_2 = [a(z_2)^2 + bz_2 + c]^{0.5}$
$P_1 = [a(z_1)^2 + bz_1 + c]^{0.5}$

where,

x,y and z are coordinates of target

that is: (x,y,z) = (x,0,1), for a 1 m target along jet centre line

N.B. the source is at: (x,y,z) = (0,0,0)

At 30°C

$f = 0.33$
$Q = 6.009 \times 10^{8}(d_j)^2$ kJ/s

and

At -10°C

$f = 0.33$
$Q = 3.819 \times 10^{8}(d_j)^2$ kJ/s

A specified radiation flux received by the target can now be calculated for any jet diameter.

Again, the three radiation intensities of concern are 4.7 kW/m², 12.6 kW/m² and 37.8 kW/m².

The distances, from the source, at which these specified intensities occur for different jet diameters are listed below:

At 30°C

Jet Diameter (m)	Flame Length (m)	Distance to Radiation Intensities (m) 4.7 (kW/m²)	12.6 (kW/m²)	37.8 (kW/m²)
1.27×10^{-3}	0.3	2.1	< 1.0	< 1.0
2.53×10^{-3}	0.5	4.6	2.7	1.4
7.08×10^{-3}	1.6	13	7.9	4.5
1.91×10^{-2}	4.3	35	21	12
2.54×10^{-2}	5.7	46	28	16
2.83×10^{-2}	6.4	52	31	18
3.81×10^{-2}	8.6	70	42	24
5.01×10^{-2}	11.3	91	55	32

At -10°C

Jet Diameter (m)	Flame Length (m)	Distance to Radiation Intensities (m) 4.7 (kW/m²)	12.6 (kW/m²)	37.8 (kW/m²)
1.27×10^{-3}	0.3	1.5	< 1.0	< 1.0
2.53×10^{-3}	0.6	3.6	2.1	1.0
7.08×10^{-3}	1.7	10	6.3	3.6
1.91×10^{-2}	4.6	28	17	10
2.54×10^{-2}	6.2	37	22	13
2.83×10^{-2}	6.9	41	25	14
3.81×10^{-2}	9.2	55	34	19
5.01×10^{-2}	12.1	73	44	22

Overfilling Automobile Propane Tank

If an automobile tank is overfilled, then the displaced propane vapour in the tank must be released into the atmosphere in order to maintain equilibrium in the tank. The propane vapour is released through a bleeder valve which is situated on the top of the tank. This release of propane vapour is an asphyxiant hazard to the person filling the tank.

This section deals with the determination of the amount of propane released as a result of overfilling and the extent of asphyxiation possible from this release.

The size of propane tanks on automobiles varies greatly. For our purposes an average size tank of 100 L of propane will be assumed. The propane tanks are filled to 85% capacity. Therefore, the amount of actual propane in the automobile tank is 85 L.

First, calculate the maximum amount of propane that can be released due to overfilling:

Total volume of liquid propane in tank is V_T:

$$V_T = 85 \text{ L} = 8.5 \times 10^{-2} \text{ m}^3$$

Therefore, total mass of propane in tank, m, is:

At 30°C

$$m = 41.40 \text{ kg}$$

and,

At -10°C

$$m = 46.16 \text{ kg}$$

Now, using equations (1) to (5), the mass of propane vapour in equilibrium in tank is m_s:

At 30°C

$$m_s = 6.000 \times 10^{-3} \text{ kg}$$

and,

At -10°C

$$m_s = 1.323 \times 10^{-3} \text{ kg}$$

Therefore, the volume of propane vapour in equilibrium in the tank, V, is:

At 30°C

$$V = 3.38 \times 10^{-3} \text{ m}^3$$

At -10°C

$$V = 6.48 \times 10^{-4} \text{ m}^3$$

Therefore, the radius of a pure propane cloud with volume V is r:

At 30°C

$$r = 9.31 \times 10^{-2} \text{ m}$$

At -10°C

$$r = 5.37 \times 10^{-2} \text{ m}$$

Now, use equation (76) to determine the distance travelled by the cloud, (ut) to render it non-asphyxiant:

Recall: the criterion level for asphyxiation is 6% oxygen.

Therefore,

At 30°C

$$(ut) = 0.48 \text{ m}$$

and,

At -10°C

$$(ut) = 0.26 \text{ m}.$$

Gasoline

For comparative purposes with propane, the hazards associated with gasoline will be evaluated.

The hazards associated with gasoline are:

- Tank Fires
- Pool Fires
- Confined Explosion
- Jet Fire

Tank Fire

Using equations (39) to (42):

therefore,

At 30°C

$m'' = 0.055\ kg/m^2 \cdot s$

and,

At -10°C

$m'' = 0.057\ kg/m^2 \cdot s$

Also, using equation (43):

(wind = 0 m/s)

At 30°C

$L = 4.94\ m$

and,

At -10°C

$L = 5.05\ m$

Now, using equations (50) to (52):

Radiation Intensity (kW/m^2)	Distance from Source Centre to Target (m) 30°C	-10°C
4.7	115	113
12.6	58	57
37.8	33	33

Pool Fire

If gasoline was released into an unbunded area, a pool fire will form. Pool fires of two different sizes were arbitrarily chosen. The diameters of the two sizes considered are 2 m and 5 m.

The analysis for determining thermal radiation effects from a pool fire are nearly identical to that used for a tank fire, except that the view factor for a pool fire is different from that for a tank fire. The view factor is different because the base of a pool would be situated on the ground, whereas, the base of a tank fire is situated at the liquid level of the tank.

Therefore, using equations (39) to (42):

At 30°C

$m'' = 0.055\ kg/m^2s$

and,

At -10°C

$m'' = 0.057\ kg/m^2s$

Also, using equation (43): (wind = 0 m/s)

At 30°C

for pool diameter = 2 m

$L = 5.26\ m$

and,

for pool diameter = 5 m

$L = 9.94\ m$

also,

At -10°C

for pool diameter = 2 m

$L = 5.38$ m

and,

for pool diameter = 5 m

$L = 10.16$ m

Now, using equations (50) to (52):

for pool Diameter = 2 m

Radiation Intensity (kW/m^2)	Distance from Source Centre to Target (m) 30°C	-10°C
4.7	102	101
12.6	62	61
37.8	36	35

and,

for pool Diameter = 5 m

Radiation Intensity (kW/m^2)	Distance from Source Centre to Target (m) 30°C	-10°C
4.7	223	221
12.6	135	134
37.8	78	77

Confined Explosion

Although gasoline does not flash like propane, gasoline evaporates into the air and forms a flammable cloud. Therefore, the rate of evaporation of gasoline from a liquid pool to the air must be calculated. This in fact has been done for a 2 m and a 5 m pool of gasoline.

Using, (Chilton and Colburn [57]):

$$j_d = (h_d/u) \cdot (C_{Bm}/C_T) \cdot (w/\rho \cdot D)^{0.67}, \quad (89)$$

where,

j_d:	j factor for mass transfer (dimensionless)
h_d:	mass transfer coefficient
u:	mean wind velocity
C_{Bm}:	logarithmic mean of C_B
C_B:	molar concentration of C_B
C :	total molar concentration
w:	viscosity of fluid
ρ:	density of fluid
D:	mass transfer diffusion coefficient

where,

$$C_{Bm} = \frac{C_{B1} - C_{B2}}{\ln(C_{B1}/C_{B2})}, \quad (90)$$

where,

C_{B1}:	initial molar concentration of species B
C_{B2}:	final molar concentration of species B

also,

$$Re_x = (u \cdot x \cdot \rho)/w, \quad (91)$$

where,

Re_x:	Reynold's Number in x-direction (i.e. wind direction)
u:	means wind velocity
x:	distance from leading edge of surface in x-direction
ρ:	density of fluid
w:	viscosity of fluid

therefore, using equations (89) and (90):

At 30°C

$u = 2$ m/s
$C_{B1} = 40.2$ mol/m^3
$C_{B2} = 31.3$ mol/m^3
$C_T = 40.2$ mol/m^3
$w = 2.86 \times 10^{-4}$ kg/m · s
$\rho = 3.466$ kg/m^3
$D = 7.76 \times 10^{-6}$ m^2/s

therefore,

$$j_d = 4.71 \times h_d, \tag{92}$$

and,

At -10°C

$u = 2$ m/s
$C_{B1} = 46.4$ mol/m^3
$C_{B2} = 44.7$ mol/m^3
$C_T = 46.4$ mol/m^3
$w = 4.11 \times 10^{-4}$ kg/m · s
$\rho = 3.994$
$D = 5.90 \times 10^{-6}$ m^2/s

therefore,

$$j_d = 8.36 \times h_d, \tag{93}$$

using equation (91),

At 30°C

$u = 2$ m/s
$\rho = 3.466$ kg/m^3
$w = 2.86 \times 10^{-4}$ kg/m · s

For 2 m pool diameter:

$x = 2$ m

therefore,

$Re_x = 4.85 \times 10^4$

From (Chilton and Colburn [57])

when $Re_x = 4.85 \times 10^4 \rightarrow j_d = 0.0042$

therefore,

$h_d = 8.92 \times 10^{-4}$ m/s

and therefore, the mass transfer rate from the pool, $\bar{m}$, is:

$\bar{m} = 1.15$ kg/s

For 5 m pool diameter:

therefore,

$Re_x = 1.22 \times 10^5$

From (Chilton and Colburn [57])

when $Re_x = 1.22 \times 10^5 \rightarrow j_d = 0.0034$

therefore,

$h_d = 7.22 \times 10^{-4}$ m/s

and therefore, the mass transfer rate from the pool, $\bar{m}$, is:

$\bar{m} = 2.33$ kg/s

At -10°C

$u = 2$ m/s
$\rho = 3.994$ kg/m^3
$w = 4.11 \times 10^{-4}$ kg/m · s

For 2 m pool diameter:

$x = 2$ m

therefore,

$Re_x = 3.89 \times 10^4$

From (Chilton and Colburn [57])

when $Re_x = 3.89 \times 10^4 \rightarrow j_d = 0.0043$

therefore,

$h_d = 5.14 \times 10^{-4}$ m/s

and therefore, the mass transfer rate from the pool, $\bar{m}$, is:

$\bar{m} = 0.74$ kg/s

For 5 m pool diameter:

therefore,

$Re_x = 9.72 \times 10^4$

From (Chilton and Colburn [57])

when $Re_x = 9.72 \times 10^4 \rightarrow j_d = 0.0035$

therefore,

$h_d = 4.19 \times 10^{-4}$ m/s

and therefore, the mass transfer rate from the pool, $\bar{m}$, is:

$\bar{m} = 1.51$ kg/s

N.B. the mass transfer rates listed above, are the maximum mass transfer rates; as the gasoline pool evaporates the mass transfer rate decreases

The maximum distance required to disperse these clouds to the LFL may be determined:

using equation (58):

At 30°C

$X_{cc} = 0.04308$ kg/m^3

For a Pool Diameter of 2 m:

$x = 20.2$ m

and, for a Pool Diameter of 5 m:

$x = 30.3$ m

similarly,

At -10°C

X_{cc} = 0.04993 kg/m³

For a Pool Diameter of 2 m:

x = 14.4 m

and, for a Pool Diameter of 5 m:

x = 21.7 m

Jet Flame

Although gasoline is not stored under pressure it is still possible to get a jet flame. Such a jet flame could occur if a leak in the dispenser hose occurred during the filling of the fuel tank in a motor car.

Using equation (79):

At 30°C

$$L = 305.2 \times d_j, \tag{94}$$

and,

At -10°C

$$L = 328.1 \times d_j \tag{95}$$

Using equation (88):

At 30°C

Jet Diameter (m)	Flame Length (m)	Distance to Radiation Intensities (m) 4.7 (kW/m²)	12.6 (kW/m²)	37.8 (kW/m²)
1.27×10^{-3}	0.4	< 1.0	< 1.0	< 1.0
2.53×10^{-3}	0.8	1.0	< 1.0	< 1.0
7.08×10^{-3}	2.2	4	3	1
1.91×10^{-2}	5.8	11	6	3
2.54×10^{-2}	7.8	14	8	4
2.83×10^{-2}	8.6	16	9	4
3.81×10^{-2}	11.6	21	12	6

and,

At -10°C

Jet Diameter (m)	Flame Length (m)	Distance to Radiation Intensities (m) 4.7 (kW/m²)	12.6 (kW/m²)	37.8 (kW/m²)
1.27×10^{-3}	0.4	< 1.0	< 1.0	< 1.0
2.53×10^{-3}	0.8	1.0	< 1.0	< 1.0
7.08×10^{-3}	2.3	4	2	1
1.91×10^{-2}	6.3	10	6	3
2.54×10^{-2}	8.3	13	8	4
2.83×10^{-2}	9.3	15	9	4
3.81×10^{-2}	12.5	20	11	6

Propane Tank Truck

If a hazard occurred when the refuelling tank truck was on the propane storage tank site, then the magnitude of the consequences from the resultant hazard could be greatly increased due to the increase in the propane inventory on the site.

The hazards of concern when the tank truck is on the propane storage site are the following:

- UVCE
- BLEVE
- Fireball
- Pool Fire
- Asphyxiation

For calculation of the safety separation distances from the aforementioned hazards the total inventory is assumed to be 60 m^3 of liquid propane; the contribution of the storage tank, to the total, is small.

The calculations for the safety separation distances with the increased inventory were performed using the identical equations used for the propane storage tank.

The results of these calculations are listed in section 8.3.

Appendix II: Plotted Values for Figures 2, 3, 5 and 6

The following are the points plotted in Fig. 2. They were determined using equation (18).

At 30°C

Distance r (m)	Overpressure $P - P_o$ (kPa)
27.6	33.329
30.0	30.615
40.0	22.962
50.0	18.369
60.0	15.308
80.0	11.481
100.0	9.185
120.0	7.654
140.0	6.560
160.0	5.740
180.0	5.103
200.0	4.592
250.0	3.674
300.0	3.062
400.0	2.296
500.0	1.837
750.0	1.225
1000.0	0.919
1500.0	0.612

The following are the points plotted in Fig. 3. They were determined using equation (18).

At -10°C

Distance r (m)	Overpressure $P - P_o$ (kPa)
20.1	33.329
30.0	22.342
40.0	16.757
50.0	13.405
60.0	11.171
80.0	8.378
100.0	6.703
120.0	5.586
140.0	4.788
160.0	4.189
180.0	3.724
200.0	3.351
250.0	2.681
300.0	2.234
400.0	1.677
500.0	1.341
750.0	0.894
1000.0	0.670

The following are the points plotted in Fig. 5. They were determined using equation (32).

At 30°C

Distance r (m)	Overpressure P (kPa)
1.69	178.312
5.0	53.005
10.0	24.421
20.0	11.252
30.0	7.151
40.0	5.184
60.0	3.295
80.0	2.388
100.0	1.861
125.0	1.450
150.0	1.183
175.0	0.996
200.0	0.857
225.0	0.752
250.0	0.668

The following are the points plotted in Fig. 6. They were determined using equation (33).

At -10°C

Distance r (m)	Overpressure P (kPa)
1.67	70.065
5.0	20.493
10.0	9.442
20.0	4.350
30.0	2.765
40.0	2.000
50.0	1.562
60.0	1.274
70.0	1.072
80.0	0.923
90.0	0.809
100.0	0.720
110.0	0.647
120.0	0.587
130.0	0.537
140.0	0.499
150.0	0.457